MEN OF RUSSIAN SCIENCE

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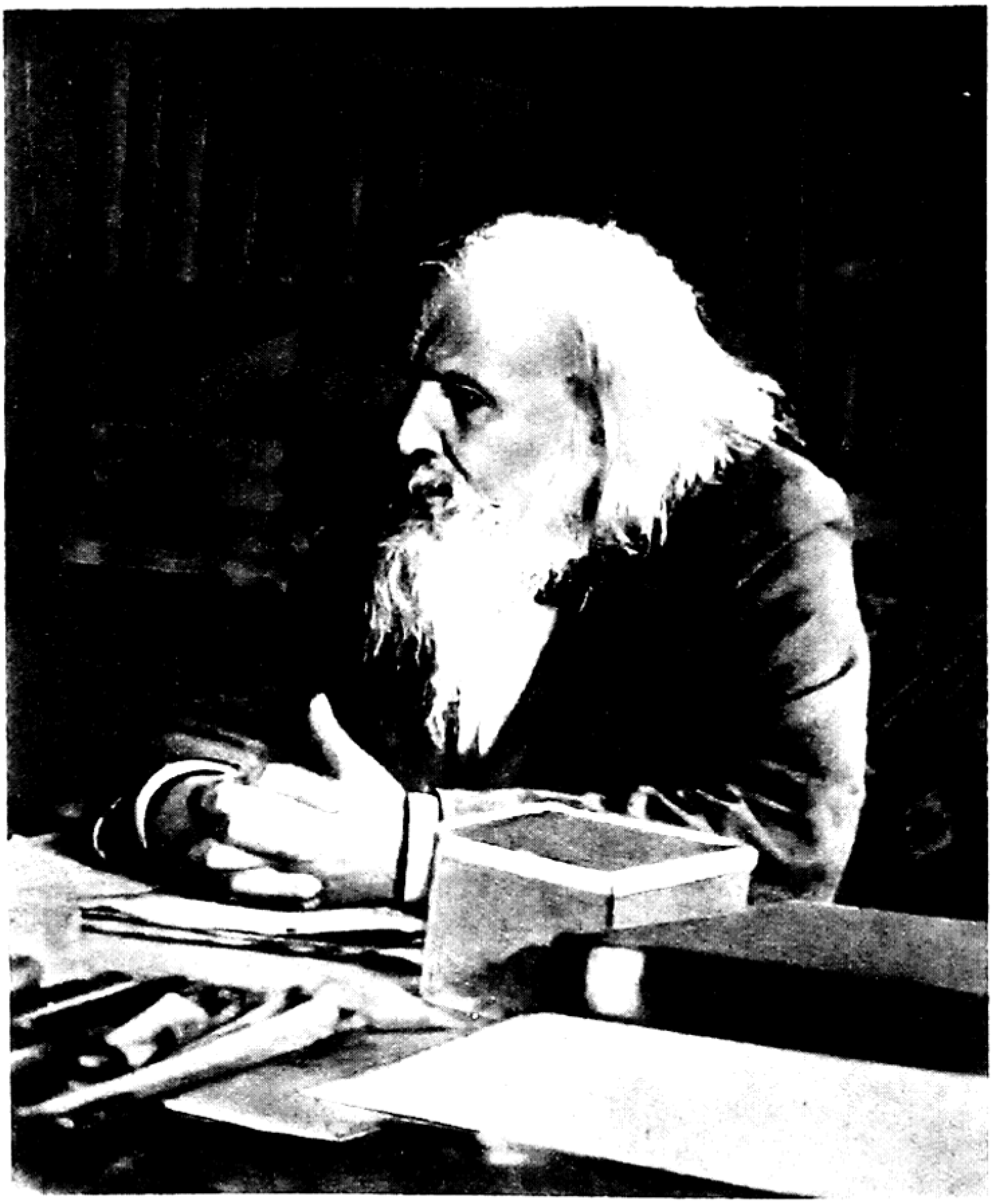

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DMITRY IVANOVICH MENDELEYEV

His Life and Work

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This book deals with the life and works of the great Russian scientist Dmitry Ivanovich Mendeleyev.

Mendeleyev's work had many features that were typical of advanced Russian natural science as a whole. He possessed a breadth of vision that led him into many fields of scientific work.

To understand nature as a single whole, and to seek the mutual relations between its phenomena, always with the aim of putting the natural law or the phenomena to the service of mankind—that was what Mendeleyev set himself and his pupils to do.

The main feature of Mendeleyev's work was the importance he attached to linking theoretical work with practice, with life. As an epigraph to his *Foundations of Chemistry* he chose the prophetic words: "What science sows the people will reap." On whatever problem he was working, all his deeds were inspired by the wish to help the development of the productive forces of his native land and to advance technique and science in Russia.

Mendeleyev attached the greatest importance to Russia's chemical industry, before which, he considered, lay the essential tasks of exploiting its salt deposits, developing the production of soda, sulphuric acid, and artificial mineral fertilizers (on the basis of its rock-phosphate) and the chemical treatment of oil and coal.

He drew up a long-term programme for exploiting Russia's extremely rich natural resources and applying chemistry to various branches of the nation's economic life. He is rightly known as the initiator of the wide application of chemistry to Russian industry and agriculture.

It was Mendeleyev who conducted the first serious agrochemical research in Russia. He established the first network of agricultural experimental stations. Supervising the work of the Chamber of Weights and Measures he prepared the introduction into Russia of the metric system.

Among the many problems dealt with in Mendeleyev's work considerable attention was paid to such problems as irrigating the soil in the Lower Volga area, the improvement of navigation, and the construction of new railway lines. The studies of the great scientist's papers that have been conducted in Soviet times have revealed the extraordinarily broad scope of his interests in many fields of science, technology, industry, agriculture and transport.

Mendeleyev always had a clear conception of the responsibility incumbent on him as a leading scientist towards Russian science and the development of his country's productive forces.

The great scientist devoted much of his powers and time to training a body of Russian scientists; under his guidance there appeared a brilliant group of scientists developing the ideas of their distinguished teacher.

The 1917 Revolution ushered in a period when all the best features of pre-revolutionary Russian science were able to flower fully. For the first time in the history of mankind science has become at once the property and the affair of the people. Intimately linked with production, respected and cherished by the public, Soviet science is helping Soviet man to transform nature.

The legacy of Russian classical thought is now being creatively developed. The treasure passed down to Soviet people by the pre-revolutionary representatives of advanced scientific views continues to multiply and grow. No better example of this could be found than the development of the work of the great natural scientist Mendeleyev.

LIFE AND WORK

Dmitry Ivanovich Mendeleyev was born on February 8, 1834,* in the Siberian town of Tobolsk. His father, Ivan, a graduate of St. Petersburg Teachers' Training College, took up teaching and in 1827 was appointed director of the Tobolsk *gymnasium*. His mother, Maria, was a woman of remarkable intelligence and energy who exercised a decisive influence on the character of her younger son Dmitry.

In the year Dmitry was born a terrible blow struck the Mendeleyev family: Ivan Mendeleyev became totally blind and had to resign his post. And though an operation two years later led to a partial recovery of his sight he was unable to return to work. The task of bringing up, indeed of supporting the large family (Dmitry was the seventeenth child) fell entirely on his wife.

From her brother, Maria Mendeleyev received a small dilapidated glass works in the village of Aremzyanskoye, some twenty miles from Tobolsk. She moved with the entire family to the village and took over the running of the works which thanks to her perseverance and energy was soon put on its feet. Various kinds of glass-ware were produced, principally pharmaceutical utensils. And in this way a prop was provided for the family's upkeep.

Young Dmitry's earliest memories were connected with the stoves that burned day and night to keep the glass molten. From friendly glass-blowers he learned many secrets of the trade. When, fourteen years later, Mendeleyev came to write his treatise for his Master of Science degree he made use of the knowledge he had acquired at the works and gave a scientific explanation of many processes of glass production.

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* All dates in the book are given according to the Old Style.

Maria Mendeleyev instilled into the young minds of her children a love and respect for work. And not without result. Dmitry Mendeleyev's conception of life was indissolubly connected with work; only work, he considered, gave life its amplitude and joy.

In 1840, when its youngest members were old enough to go to school, Maria Mendeleyev brought the family back to Tobolsk. There the Mendeleyevs found themselves in a progressive society, for in Tobolsk lived many participants in the Decembrist rising exiled by Nicholas I. Basargin, one of these exiles, was later to marry Dmitry's sister Olga.

In 1841, at the age of seven, Dmitry started going to the Tobolsk *gymnasium.* He at once distinguished himself by his ability and brilliant memory. His inclination lay towards mathematics, physics and geography, subjects which however in the classical *gymnasium* were considered less important than Latin. Mendeleyev was never to forget how at the end of the term his schoolmates propped Popov's *Latin Grammar* up against a tree and flung stones at it. He had every sympathy for them, for he shared their hatred of that dead language, and for all the help his father gave him, he often got low marks in Latin.

Later, in his comments on "Public Education," Mendeleyev wrote that when he recalled the influence of his teachers at the *gymnasium* there were always two on whom his memory dwelt—I. K. Rummel, the mathematics and physics teacher, and M. I. Dobrokhotov, the history master. "Whenever I discuss this subject with intelligent and thoughtful people," he wrote, "they always refer to one or two teachers who have had a lasting influence on their lives."

But of all the influences on Dmitry the strongest was that of nature, to which he remained devoted throughout his life. In the company of his school tutor Pyotr Yershov, who wrote the well-known fairy-tale *The Little Hump-Backed Horse*, he took long walks, during which he collected stones, flowers and insects.

The boy's successes in his studies, specially in the senior classes, delighted his mother who waited impatiently for the day when her cherished dream of giving her favourite son higher education would be fulfilled. And Dmitry, too, shared this dream of studying at Moscow University where so many prominent Russian scientists taught.

But in 1847 further misfortune befell the Mendeleyev family: Dmitry's father died, and this was soon followed by the death of his elder sister. The older children then left Tobolsk while Maria Mendeleyev remained with the two youngest, Dmitry and Liza.

Two years later, in 1849, Dmitry left school. The question of his further studies arose. His mother had no longer anything to keep her in Tobolsk and on the advice of friends decided to leave for Moscow.

They made the journey in the summer of that year—a journey of many thousands of miles in a horse-drawn coach, which left an indelible impression on Mendeleyev's memory—the virgin forest, the rolling steppe, the picturesque rivers.... Already a picture of the boundless wealth of Russia was forming in the future scientist's mind.

Dmitry Mendeleyev came to Moscow with an ardent desire to study, but Moscow gave him a chill welcome: he was unable to enter the university as regulations restricted entry to those who had studied in *gymnasiums* within the Moscow area.

With considerable difficulty Mendeleyev managed to gain entrance to the mathematics and natural sciences department of the Main Teachers' Training College at St. Petersburg. His mother settled in the city with her daughter so as to be near to her son but died in September 1850 as the result of a chill. Mendeleyev was deeply shaken by this loss. Eighteen months later his sister Liza died. The young man was left alone in St. Petersburg.

Mendeleyev held the memory of his mother in lifelong reverence. His feelings are clearly expressed in the touching dedication to his *Study of Aqueous Solutions by Means of Specific Gravity*, published in 1887: "This study is dedicated to the memory of my mother by the youngest of her children. She was able to rear him only at the cost of her own labour in charge of a works; she educated him by her own example, she corrected his errors by her love, and, in order to wed him to science, she brought him from Siberia, expending all that remained of her means and her physical strength. Her last testament to him was to bid him avoid illusions, to persist in work and not in words alone and patiently to seek the divine or scientific truth; for she understood . . . how much more there remains to be discovered and how with the help of science, with love, not with violence, but with firmness we shall eliminate prejudice and error and achieve the protection of the truths that have been won, freedom for further growth, general welfare and personal satisfaction. This maternal behest is considered as sacred by D. Mendeleyev."

In those days the mathematics and natural sciences department at the Main Teachers' Training College was quite different from its other departments as it was from similar departments at other colleges. Few subjects were read and consequently the teaching staff was relatively small; on the other hand each chair was held by a teacher of distinction and high scientific qualification. These teachers made every effort to give their pupils the broadest possible scientific outlook. "How delightful it would be to enter that place again where I first tasted the sweet pleasure of work," wrote Mendeleyev a year after he graduated.

The strongest influence in the formation of the personality of the future scientist was that of Professor Alexander Voskresensky, the distinguished chemist and teacher from whose instruction a brilliant company of Russian chemists benefited. To his many pupils, who included Mendeleyev, Beketov and Sokolov, Voskresensky was known affectionately as "the grandfather of Russian chemistry." While working as a chemist Voskresensky gave much time to the education of the younger generation. He had a happy aptitude for noticing any particular bent a student might possess and for developing it with the patience and enthusiasm of a great teacher. What he valued above all in his students was originality; he made every effort to implant in them an independent outlook. He taught them to think boldly and to overcome all obstacles that might arise on their path. "Others often used to talk about the great difficulties in scientific work but when we were in Voskresensky's laboratory we used to hear most often his favourite saying: 'It is not the Gods who bake the pots and make the bricks,' " Mendeleyev wrote in the biography of his teacher.

Mendeleyev was also strongly influenced by Mikhail Ostrogradsky, Stepan Kutorga and other professors. It was Ostrogradsky who made him so enthusiastic a student of mechanics and mathematics. In an article "On Mendeleyev's Work on the Resistance of Liquids and Aeronautics," N. E. Zhukovsky, the founder of aviation in Russia, gave an enthusiastic appreciation of Mendeleyev's research in the field of jet mechanics. Professor Kutorga who gave a geology course in the institute enthralled his listeners by his striking gift of exposition. He was a man of many parts and an original researcher into the secrets of nature. In Mendeleyev's study preserved in the U.S.S.R. Institute of Weights and Measures in Leningrad one may see the neatly bound and carefully illustrated note-books in which Mendeleyev kept a faithful record of the impressions made on him during summer mineralogical and botanical trips undertaken with his teachers, Professors Kutorga, Shikhovsky and Brandt.

Drawn above all to natural science Mendeleyev paid special attention to chemistry. With remarkable tact and skill Professor Voskresensky implanted in the young man an interest in independent scientific work in chemistry. "As one of Voskresensky's pupils," wrote Mendeleyev, "I clearly remember the delightfully natural frankness of his exposition and that constant encouragement of scientific research carried on independently, with which Voskresensky recruited much new strength into chemistry."

Voskresensky boldly led his students into the world of conflicting ideas. Chemistry was going through an exciting stage. Passionate arguments were in progress in which fundamental conceptions of chemistry, conceptions of valency, of the molecule and the atom that are now accepted as axiomatic were being thrashed out.

Dalton's Law of Multiple Proportions, discovered in 1804, played a great part in the development of the scientific conception of the atom. This law led to the necessity of recognizing the existence of discrete, separate particles in substances. The next important stage in the development of chemistry opened with the work of Berzelius, one of the major figures in chemistry before Mendeleyev. Studying the influence of the electrical field on various elements in solution he proved that the atom possesses electrical properties. Berzelius's study of the decomposition of various substances when subjected to the action of electric current led him to the supposition that "every compound body, no matter the number of components, may be divided into two electrically different components." According to Berzelius the atom itself had two opposite electric poles, in one of which the electricity was present in a "more concentrated" form so that the atom was not electrically neutral. Hence he explained the possibility of chemical reciprocity between different atoms.

Berzelius and his followers found a fair number of chemical substances that gave striking proof of the correctness of these new electrochemical views. But in his enthusiasm Berzelius imparted an absolute significance to electrochemistry—applying it in a metaphysical spirit to all chemical combinations including organic ones. Berzelius's theories were bound to lead him to a dead-end since they did not correspond to the law of the conservation and transformation of energy and to Faraday's electrochemical laws.

It was the French chemists, Dumas and Laurent who dealt the first blow at the Berzelius theory. They showed that in the compound organic substance naphthalene, hydrogen, which gives a positive electric reaction can be replaced by chlorine, which gives a negative reaction. This contradicted the Berzelius principle.

Further research led to the discovery of many more reactions of this kind.

Berzelius began to dispute the question. In each case he tried to find an imaginary compound combination of positive and negative particles. But you cannot foist on to nature laws that are not supported by the results of experiment. In the struggle with the narrow views of Berzelius the fundamental conceptions which enabled chemistry to advance were hammered out.

Mendeleyev was attracted to chemistry not only because it was the arena of struggle for a true understanding of nature. Chemistry embodied his lifelong dream to place simple, cheap, readily available, commonplace substances at the service of man. He made up his mind once and for all to be a chemist.

While still studying, Mendeleyev made original contributions to chemistry. His first scientific research, *The Analysis of Finnish Allanite and Pyroxene*, was considered worthy of publication by the Mineralogical Society.

In 1854, the twenty-year-old student completed a serious work of major research into isomorphism, the process in which similar elements replace each other in some chemical combinations without changing their crystalline form. By plunging the crystals of one isomorphous substance into a solution of another substance it may be observed that new layers, composed of atoms of the isomorphous substance in solution, form on the surface of the crystals that have been introduced into it. Mendeleyev used natural minerals to study the phenomenon of isomorphism, preparing in the laboratories of the institute crystals of the same group of symmetry of the most varied substances. He noted with interest that the isomorphic substances crystallize out of solutions in the form of mixed crystals of uniform structure.

In his study of isomorphism Mendeleyev strived to understand the connection between the atoms of isomorphic substances; he rightly considered the study of this connection to be one of the main tasks of chemistry.

Somewhat forestalling events we should here point out one important feature of this, Mendeleyev's first scientific work. The phenomenon of isomorphism which attracted the young scientific worker's attention clearly reveals the similarity in behaviour of atoms of different elements. Later, Mendeleyev referred to isomorphism as one of the most important characteristics on the basis of which elements may be grouped in their natural order.

Intense work took a toll of Mendeleyev's health; in 1853 he suffered from a throat haemorrhage so severe that fears were expressed for his life. He lay for long in the institute hospital. But although treated as a serious case with only a short time to live, Mendeleyev astonished everyone by his unfaltering resolution, his will power and extraordinary capacity for work. Not for one day did he interrupt his studies in hospital; and his work was always awarded high marks.

The question arose at the institute of sending Mendeleyev to Kiev University, where, it was thought, the change of climate would be good for his health. Mendeleyev, however, refused to leave St. Petersburg. It would have meant losing the scientific assistance and personal friendship of his beloved Professor Voskresensky under whose guidance he had already conducted several research works.

In 1855 Mendeleyev took a brilliant degree at the Teachers' Training College, being first of his year and the winner of a gold medal. The examiners were unanimous in congratulating Voskresensky on his gifted pupil. Many had the insight to recognize in the young man, who but yesterday had been a student, the lineaments of the future genius of research. There were grounds for that assessment in Mendeleyev's first scientific work, the results of which he published as his diploma thesis with the title "Isomorphism in Connection with Other Relations between Crystalline Forms and Chemical Constitutions." This work was published in 1856 in the *Gorny Zhurnal* (*Mining Journal*), and soon afterwards as a separate brochure. In his notes to his bibliography, published in 1889, Mendeleyev wrote: "At the Main Teachers' Training College we had to write a thesis on a subject of our own choice. I chose isomorphism because I was interested in the things I had discovered in 1 and 2,[*] and the subject seemed to me important from the natural science and historical point of view.... In preparing that thesis I was involved most of all in studying chemical relations. This meant very much to me. It was written in 1854-55."

After graduation, Mendeleyev remained at college to prepare for his Master of Science degree. But the devel-

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[*] These numbers refer to the bibliography in which Mendeleyev's student works are included. 1. *Chemical Analysis of Finnish Allanite* and 2. *Pyroxenes from Ruskiala, Finland.*

Professor A. A. Voskresensky

Mendeleyev in the year of his graduation (1855) opment of his illness did not permit him to remain in St. Petersburg. The doctors strongly recommended him to go to the South. Circumstances favoured this plan. In July, 1855, teaching posts fell vacant in two southern cities, Odessa and Simferopol. As a gold medallist Mendeleyev had the right to choose his place of employment. The choice was not difficult. In Odessa there were a *lycée* and an excellent library with all the works he required for preparing his exams. Simferopol offered no such amenities. So it had to be Odessa. However, by some "mistake" on the part of the Ministry of Education Mendeleyev's name was muddled with that of a certain Yankievich to whom the coveted Odessa post went unexpectedly. Neither the intervention of the college authorities nor Mendeleyev's own protests helped in the matter and on August 25, 1855, Mendeleyev left for Simferopol.

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At that time the Crimea was one huge military camp. Russia's armies were locked in battle with the combined forces of Britain, France and Turkey, the invaders of Russia. The brunt of the fighting was borne by the fortress city of Sevastopol.

In the heroic defence of Sevastopol the Russian people wrote one of the brightest pages in the history of their land. For over eleven months the city withstood siege. The gay flourishing southern city was reduced to ruins overhung by frowning bastions. The near-by town of Simferopol became a military base, filled with hospitals, ammunition dumps and food stores. Sevastopol fell in August 1855, but officially the state of war continued and Simferopol remained on a military footing.

In Simferopol, Mendeleyev met the famous Russian surgeon Pirogov who disposed of the erroneous conception that Mendeleyev had about the nature of his disease. Instead of the supposed neglected tuberculosis Pirogov at once diagnosed the presence of a valvular defect of a non-mortal character and restored the young scientist's belief in his power of life. Later, Mendeleyev often recalled the great surgeon. "There was a doctor," he would say with fervour. "He could see through a man; he understood my nature in a flash."

Because Simferopol was under martial law the school to which Mendeleyev had been appointed did not reopen that autumn. Life in the town was expensive and uncomfortable. So when the weather broke, Mendeleyev took his holidays and left for Odessa. "I set out from Simferopol on October 30th," he wrote to his brother, "wearing a short fur coat that offered poor protection against the night frosts, bearskin boots, and a tall fur hat. I drove from the Crimea with a month's salary in my pocket and hope in my heart. . . ."

Mendeleyev found favourable conditions in Odessa and it was not long before he received a teaching post at the First Odessa Gymnasium attached to the Richelieu *lycée*, one of the oldest educational establishments in Russia.

The Crimean war had little effect on the life of Odessa. In this important cultural centre with its *gymnasiums* and its university—known as the Novorossiisk University—where many prominent Russian scientists, including Mendeleyev's "saviour" Pirogov, worked—the young research worker experienced a burst of new strength. Full of enthusiasm, he threw himself into his work in the university laboratories and library. There he prepared his Master of Science thesis on *Specific Volumes.**

In this work, it should be noted, Mendeleyev for the first time raised the important question of principle on the nature of solutions. He was to deal more fully with the question in his *Combination of Alcohol and Water* (1865) and *Studies of Aqueous Solutions by Means of Specific Gravity* (1887), works which resulted in the establishing of the hydrate theory of solutions, now universally accepted.

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* Specific volume is the space which contains the proportionate quantities of elementary bodies capable of substituting for each other in chemical compounds. In those times the study of the reaction of substitution had much importance for chemistry.

Mendeleyev was also doing valuable research into gases. Later, the great scientist frequently underlined the role of his early work in the discovery of the Periodic Law. "Isomorphism, that is, the capacity of different substances to give similar crystalline forms," he stated, "is one of the typical properties of the elements in one and the same chemical group.... In the same way, specific volume, that is, the reciprocal of density gives, as I observed later, one of the most striking examples of periodicity, the recurrence of properties of simple bodies arranged in order of their atomic weights."

Working with great enthusiasm and concentration, Mendeleyev in a remarkably short time—no more than a month—completed his work *Specific Volumes*, which also served to prepare him for the examinations for his Master of Science degree.

* * *

So Mendeleyev had finished this important piece of scientific research. No longer haunted by the fear of illness he left hospitable Odessa in May 1856. The same month he presented himself in St. Petersburg for the examinations for his degree as Master of Science. This was another brilliant success; he received the highest marks in all papers. Now all that remained was to put his thesis into final shape.

For his degree, Mendeleyev presented the thesis on *Specific Volumes*. The official announcement of the occasion, as published by the Ministry of Education, runs:

"On Sunday, September 9, at 1 p. m., in the St. Petersburg University, D. Mendeleyev, a former pupil of the Main Teachers' Training College, and at the present time a senior teacher of natural sciences at Odessa Gymnasium, presented his thesis on specific volumes and related subjects.... The candidate's own experiments and the conclusions he drew from them were received with general approval: they offered the possibility of distinguishing by volume in the solid state the phenomenon of substitution from the phenomenon of combination and *pointed the way to the natural classification of chemical combinations* on the basis of their specific volumes." The anonymous writer of those lines prophetically underlined the importance of Mendeleyev's research for further work concerned with the discovery of the Periodic Law.

The Council of St. Petersburg University was unanimous in its decision to confer on Mendeleyev the degree of Master of Physics and Chemistry.

Three days after presenting his thesis Mendeleyev applied to the university for permission to present the following week his preliminary report on "The Structure of Siliceous Combinations." This was necessary if he was to receive the post of assistant professor and the right to lecture in the university. With permission obtained, Mendeleyev set to work and on October 21, 1856, in little more than a month after he had presented his first thesis, presented a second—"The Structure of Siliceous Combinations."

In the following January, at the age of twenty-three, Mendeleyev was appointed a reader in chemistry at St. Petersburg University and began his course of lectures.

Although he was kept extremely busy with teaching and administrative work (he was elected secretary of the department) Mendeleyev continued his research work in the university laboratory. His results were published in the form of a number of articles in Russian and foreign learned journals.

The laboratory where Mendeleyev worked was part of the university building, occupying two small rooms with stone-flagged floors and empty shelves. The rooms were so poorly ventilated that it was impossible to stay in them for long during experiments: the chemist had to make frequent dashes out into the fresh air, often into the rain or snow. As for the equipment, it scarcely deserved the name. In those times there was not a test-tube to be found in the shops of St. Petersburg. The laboratory workers had to make even their own rubber tubes. The funds allotted for the upkeep were totally inadequate. There was a popular saying among chemists of those days that the worse the laboratory the better the research done in it. This was usually said with reference to the Kazan laboratory where the well-known Russian chemist and member of the Academy N. N. Zinin was doing pioneer research. Zinin transferred to the St. Petersburg Academy of Medicine and Surgery, but here too the grant received by the chemistry laboratory was only 30 rubles a year. With this wretched equipment, scientific workers had to cope with problems of great difficulty and variety. The discrepancy between the tasks and the means for fulfilling them was a serious hindrance to the development of chemistry. Changes were necessary, and Mendeleyev took up his pen to try to bring them about.

Mendeleyev decided to popularize contemporary scientific problems, partly to attract the public's attention to the difficulties facing science. For this purpose he took charge of the department of scientific information in the *Journal of the Ministry of Education*. He published a series of articles in this magazine. The titles he gave them were very modest, such as "Liquid Glass, or Glazes and the Methods of Applying Them," or "New Dye-Stuffs," etc. All these articles were inspired with the same idea, that the development of science is closely connected with the development of production, and that without the development of science there can be no industrial development. "The effort to use the abstract theories of science in real life," Mendeleyev wrote in this journal, "is a notable feature of our times, a great step forward. This beneficient connection between science and life is the reason for the enormous successes of contemporary society, that remarkable advance of which the 19th century may be justly proud."

Mendeleyev remained faithful throughout his life to the cause of developing science in his native land as he was to that of keeping science in touch with life.

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By the end of the 1850's Mendeleyev was already considered the natural successor to such leading Russian chemists as Zinin and Voskresensky. The time had come for him to prepare for a professorial chair. For this he would have to conduct some important piece of research. But St. Petersburg did not have either the laboratories or the apparatus for the work he had in mind. He came to the reluctant conclusion that he would have to go abroad. In January 1859, he was officially informed that he could go to Germany for two years' work, "for the improvement of his scientific knowledge," and when term ended three months later, he left for Heidelberg; many distinguished scientists including Kirchhoff and Bunsen were working there at that time.

At first, Mendeleyev considered working in Bunsen's laboratory. But, after all, he was no shy beginner, but a mature scientific worker with important independent work to his credit. Had he worked in Bunsen's laboratories he would have to abandon many of his own scientific plans since the interests of the two researchers ran along different lines. Bunsen and his friend Kirchhoff were then engrossed in work on spectral analysis. Mendeleyev's interest, on the other hand, centred on other problems and he saw no reason whatsoever to change the main direction of his own scientific studies in pursuit of which he had come abroad, like so many other outstanding Russian scientists who were unable to obtain suitable conditions for original experiment in their own land.

Mendeleyev found that at Heidelberg there were places making laboratory equipment and chemical reagents; he decided to use the slender means he had been provided with on leaving St. Petersburg to organize his own small laboratory.

He set about the job with ardour. He bought and ordered the necessary apparatus, made to his own specifications, had gas installed in his rooms, one of which he fitted up as a laboratory.

The best craftsmen of those times prepared Mendeleyev's apparatus. Geissler—a past-master in glass-ware—made him special thermometers and pyknometers (instruments for determining the specific gravity of liquids). One of these pyknometers, designed by Mendeleyev, became widely used in laboratory work under the name of the Mendeleyev pyknometer.

In his new laboratory, Mendeleyev gave himself up entirely to his next piece of research. "Most of the time I spent abroad," he wrote to the university, "was devoted to studies in that special field where chemistry merges with physics and mechanics. Being convinced of the identity of power of chemical affinity with that of cohesion, and convinced that a complete solution of the problem of the reasons for chemical reactions cannot be reached unless we know the degree of molecular cohesion, I chose to specialize in this field where so little has yet been done."

Mendeleyev carried out delicate experiments in the study of phenomena connected with capillarity and he rightly saw in them examples of the operation of the cohesive forces between molecules. The results of this work appeared in three articles: "The Capillatory Properties of Liquids," "The Expansion of Liquids" and "The Temperatures of Absolute Boiling Points of the Same Liquids."

It would be difficult to exaggerate the importance of these works. The prevailing view in those times was that there were two kinds of gases—those which could be condensed to liquid form and those which could not be condensed—the "constant" gases such as nitrogen, oxygen, hydrogen, methane, carbon monoxide, etc. By his experiments Mendeleyev was the first to reveal the error in dividing gases in this way.

As is generally known, the level of liquids in capillary tubes rises as the result of the attraction between the molecules of the liquid and also between the molecules of the liquid and those of the wall of the tube. If the liquid moistens the walls of the tubes then the molecules of the liquid that have risen and adhered to the side attract by the force of cohesion adjacent molecules and thus cause the column of liquid to rise to a specific height. "The product of the density of the liquid and the height of its rise in a capillary tube (of certain diameter) gives us a way of measuring the degree of cohesion," wrote Mendeleyev.

Cohesive force may be weakened or altogether eliminated. All that is required is to heat the liquid under examination. As the temperature rises molecular cohesion diminishes and the level of the liquid in the capillary tube falls. At certain temperatures molecular cohesion disappears.

"When cohesion reaches zero," wrote Mendeleyev in formulating the laws of his findings, "the liquid should become a body possessing no cohesion—a gas, i.e., it should vaporize despite the small space it is enclosed in." And further: "... any liquid (in a closed thick-glass tube) at a certain temperature should instantly vaporize and remain in that state in spite of the increased pressure. This temperature is known as absolute boiling point precisely because it is independent of pressure." Mendeleyev showed that every liquid has its own strictly determined absolute temperature. This temperature was later given the name of the critical temperature. By experimental methods he established the critical temperature of various liquids. Now it became clear to him why researchers had been unable to liquefy a number of gases even by using super-high pressures. No matter how much pressure it is submitted to, a gas cannot be liquefied above its critical temperature. "The non-liquefaction of well-known gases such as nitrogen, oxygen and hydrogen is probably due to the fact that experiments were conducted at temperatures above the absolute boiling point. The more the gases selected for liquefaction are cooled the greater our hopes of being able to liquefy them."

These remarkable ideas were put on record by Mendeleyev in 1860, some nine years before the work of Thomas Andrews, the Irish chemist, to whom some historians of physics give an unjustified priority in this field.

Following the way indicated by Mendeleyev, researchers were later able to "lead" all gases through their critical temperatures and liquefy them. We know that from liquefied air nitrogen and oxygen are obtained. By the fractional freezing of natural gases and from the air itself we obtain rare gases. Nowadays the production of liquid gases and their components involves a number of branches of industry which owe their foundation and growth to Mendeleyev.

The little time that Mendeleyev allowed himself for leisure after his laboratory work he spent with his friends —he was on close terms with several young, talented, and then still little known Russian scientists who were also working at Heidelberg. Among them were Beketov and Savich the chemists, Borodin the chemist-composer, Sechenov the physiologist, Botkin the doctor, and Vyshnegradsky the mathematician and mechanical engineer. This small Russian colony of scientists was a friendly group. "At Heidelberg, soon after my arrival," wrote Sechenov in his autobiographical notes, "I found a great company of Russians: my friends from Moscow the family of

T. P. Passek (mother with three sons), Savich the chemist, who was working under Erlenmeyer, three young people about whom nothing was heard later, and, just the opposite in this respect—Dmitry Ivanovich Mendeleyev. Later—in the winter, I think—A. P. Borodin arrived. Mendeleyev, of course, was the leader of our circle if for no other reason than the fact that, though so young (younger than me), he was already a qualified chemist while we were still students."

With Borodin, Mendeleyev made several interesting trips to Switzerland and Italy. The friendship that he struck up with the composer, as with Sechenov, Beketov, Olevinsky and Vyshnegradsky lasted into the times of their return to Russia.

In a letter to Shishkov the chemist, Mendeleyev wrote: "Of the Russian chemists abroad I have come to know Beketov, Abashev, Savich and Sechenov. Except for Abashev they are men who do honour to their country; I am delighted to call them my friends."

This friendship was cemented by their common devotion to the cause they served, to their work. And this enriched the life of each of these remarkable people.

In the autumn of 1860, Mendeleyev took an active part in the work of the First International Congress of Chemists, which was held in Karlsruhe. Among chemists participating in the congress were also Zinin, Shishkov, Borodin, Savich, Lesichevsky and the Polish chemist Natanson. Zinin, Mendeleyev and Shishkov were members of the principal working organ of the congress—the committee that drafted the resolutions.

This congress—the first world gathering of chemists—played an important role in the history of chemistry.

Chemistry was still passing through difficult times: there was not even general agreement among scientists on the fundamental conceptions of the science. "Some understood by the term equivalence the quantity of elements that replaced each other without a change in their basic properties; others considered equivalence to be the share—i.e., the weight ratio of chemical compounds; and, finally, there was a third group that maintained that a consistent view about equivalence was quite out of the question, that it only led to confusion. Some wanted to define the particles of each substance by acknowledging only the chemical properties, i.e., reactions; others thought it necessary to recognize only the physical characteristics; and a third declared both aspects to be identical," wrote Mendeleyev from Karlsruhe to his teacher Voskresensky. The task of the congress was to clear up this confused situation.

The aims of the congress were set out in an address as follows: "By means of discussion ... to dispose of certain misunderstandings and to facilitate agreement on the following points: A more precise definition of the conceptions designated as: Atom, Molecule, Equivalence, Atomicity, Basicity, etc.; research ... into the real equivalence of substances and their formulas; the establishment of uniformity in designations and more rational nomenclature."

This address, which was intended to be a brief resumé of the programme of work at the congress, was signed by most of the leading chemists in the world. For Russia it was signed by Zinin, Beketov, Sokolov and Engelhardt.

When, later, he analyzed the significance of the congress Mendeleyev wrote: "Turbid confusion reigned.... In 1860 the chemists of the whole world gathered at Karlsruhe to reach accord and uniformity. I attended the congress and remember well how great was the difference of opinions...."

The congress served to reinforce the progressive scientific outlook that Mendeleyev had formed as the result of many years of hard work. In February 1861, he returned to Russia. On arrival at St. Petersburg he eagerly returned to the teaching work at the university that had been interrupted two years previously. He began a new course of lectures on organic chemistry and, at the same time, taught chemistry at the military school, the College of Engineering and the Transport Institute. His teaching activities, however, did not interfere with his scientific work.

While holding his course on organic chemistry Mendeleyev felt the need to prepare a text-book that would provide a clear and consistent explanation of the material of this branch of science in the light of the latest theories. As the basis of this book he decided to take the new outlook on chemistry which he called "unitary." He worked day and night at the high writing-desk which is now preserved in Mendeleyev's study at Leningrad State University. There, in two months he wrote his text-book *Organic Chemistry*—the first original university manual on the subject written in Russia.

Mendeleyev's new work met with general approval. At the suggestion of N. N. Zinin the author was awarded the Demidov Prize of the Russian Academy of Science for it. As in his previous works Mendeleyev turned his attention primarily to the general laws governing the interaction of atoms. In *Organic Chemistry* the main task he set himself was not merely to describe the known organic combinations but to show how the more complicated of them are formed from the less complicated and how they react among themselves. "The main thing for the natural chemical system ought to be their mutual relations according to their origin and chemical character, and not just one or two physical properties..." Mendeleyev wrote in formulating his new principle for explaining the extensive material collected by organic chemistry.

Entering into chemical relationship, atoms form molecular structures more or less complex in character. Each atom possesses a quite definite property of combining with this or that number of other atoms, or, as is said, a definite valency. Mendeleyev sought to use this property of the atom "both for comparison and systematic description and for studying the reactions of substances."

There was a further important aspect of *Organic Chemistry* which distinguished it from most text-books of that time—and not only of that time. With all the ardour of a materialist investigator, Mendeleyev struck out at the vitalists—those who sought a peculiar, exclusive "vital force" on which organic matter was somehow dependent for its existence. This "vital force," the vitalists maintained, was something divine and providential in origin and communicated to the phenomena of life their essential quality of unfathomability, something not to be reproduced in laboratory conditions. In contrast to the idealists, Mendeleyev taught in his *Organic Chemistry* that "every living phenomenon is the result not of some peculiar force or peculiar reason, but of the general laws of nature. There is not one living process, taken separately, that may be attributed to a peculiar power." Mendeleyev was a materialist from the very start of his scientific career, and as such he was supported by the whole progressive body of Russian science. It suffices to recall the remarkable work of Sechenov the physiologist, who had great influence on his friend Mendeleyev. Sechenov's works were inspired by the idea that "living chemical processes in the animal body are subjected to the general fundamental laws of the chemical transformation of matter." At the same time Sechenov in no way denied the originality of living phenomena. According to his definition "the physiologist is a physico-chemist who deals with phenomena of living organisms."

Studying the different ways of atoms uniting to form molecular combinations, Mendeleyev raised in *Organic Chemistry* a new interesting problem which was soon afterwards resolved in Russia by another prominent chemist, Mendeleyev's colleague A. M. Butlerov.

A large number of substances of the same chemical composition but with different properties are known to science. This is known as the phenomenon of isomerism. The existence of isomers was considered highly enigmatic. Only after Butlerov, in 1861, had established the theory of the chemical constitution of organic substances was the problem solved. Butlerov showed that the properties of a substance depend not only on its atomic composition but also on the arrangement of its atoms in molecules, and on the mutual connections between the atoms. Isomers differ from each other in the arrangement of the atoms. Butlerov's theory provided the basis for the development of organic chemistry. Armed with the theory of chemical constitution chemists were for the first time able to describe a wide range of properties of a substance in terms of molecular structure, by using what is known as the structural formula.

Here mention should be made of the striking manner in which Mendeleyev expressed his high assessment of the achievements of Russian science. Delighted at Butlerov's success he wrote to the Council of St. Petersburg University requesting that the chair of organic chemistry which he himself occupied should be given to Butlerov. His letter ran: "A. M. Butlerov is one of the most distinguished of Russian scientists. He is Russian in his scientific formation and in the originality of his work. A pupil of our famous Academician Zinin he became a chemist not abroad but at Kazan where he continues to develop an original school of chemistry. His scientific work is not just a continuation or a development of the ideas of his predecessors; they are all of his own. Chemistry has its Butlerov school, its Butlerov trend."

Mendeleyev was never the kind of scientist who is tied to his study, laboratory or lecture-room. He never admitted the division of science into a "higher" theoretical branch and a "lower" branch of practical science. He did not spare his indignation when he condemned those practising scientists who asserted that they "did not need theory but reality."

"Any 'theoretical' conception," he wrote, "which is not on a level with life, which does not correspond in reality, experiment and observation is either mental gymnastics or pure nonsense and has no right to be called knowledge. In our days only that which represents the harmony of 'theory' and 'practice' can be called knowledge in the strict sense of the word."

This idea runs through all Mendeleyev's work.

As we have seen, the young scientist, when taking but his first steps in his chosen field of knowledge and carrying out research into theoretical questions connected with the very foundations of chemistry, had defended the thesis "The Structure of Siliceous Combinations"—a work in which he dwelt in detail on the chemistry of glass-making. While lecturing on chemistry at several institutes Mendeleyev started to edit a large manual of general technology. This course translated from a foreign language was virtually rewritten by Mendeleyev who introduced an enormous amount of factual material taken from the experience of Russian industry. In 1862 there appeared the first issue of *Technology* including those chapters which in the view of the publishers were "of most practical significance in Russia," the chapters concerning the "processing of agricultural produce."

Mendeleyev's work in the field of chemical technology gave him the right to the title of professor. In 1864 young Professor Mendeleyev took over the chair of technological chemistry at St. Petersburg Technological Institute. From that time on while devoting much attention to teaching and to public affairs, Mendeleyev maintained a keen interest in the development of Russian industry.

In the middle of 1867, Mendeleyev was invited to join the committee for organizing the Russian pavilion at the World Industrial Exhibition in France; he left for Paris to make various arrangements. However, he did not confine his stay to the capital; he travelled widely in the provinces, acquainted himself with France's chemical industry, and later made several trips to visit factories in Germany and Belgium. The result of these frequent journeys appeared in the form of a large book entitled *The Current Development of Certain Chemical Industries in Application to Russia. The World Exhibition of 1867.* So simple was the language in which this book was written that anybody could read it even without a specific knowledge of chemistry. That indeed was Mendeleyev's intention. He felt it to be his task to make himself the propagandist of new scientific and technical discoveries and investigations and to get them introduced into Russian industry. It was quite natural that in this book the Paris exhibition took second place to the author's impressions of his visits to French, German and Belgian factories.

While advocating the creation of a domestic chemical industry in Russia, Mendeleyev pointed to the country's vast natural resources in raw materials. He spoke of the bitterness he felt in recognizing that Russia with all its wealth of natural salts, limestone and pyrites—the materials required for the production of sulphuric acid—left its own raw materials untouched in the ground and preferred to import ready-made products based on these same materials from abroad. Valuable forests were being barbarously burned down to get ash for soap production. But Mendeleyev not only condemned the backwardness of Russia, he pointed the ways to overcome it and in his book described a long list of chemical industrial processes, particularly the production of soda, so necessary for the development of such important branches of industry as textiles, glass manufacture, etc. He gave much practical advice for the organizing of chemical works, even calculating the profits to be got out of various processes.

Being interested in questions concerning oil formation and its extraction in Russia, Mendeleyev had, in 1863, undertaken a journey to the Baku oil-fields—no light undertaking in those days of poor roads. He made a detailed study of the state of oil extraction and of the

N. N. Zinin

A. M. Butlerov

work of the small refinery at Surakhani, near Baku. This was the beginning of Mendeleyev's fruitful work in connection with the development of Russia's oil industry. Writing about the contemporary development of certain chemical industries in Russia, Mendeleyev naturally could not avoid including his impressions of Baku, and in setting them down in detail in his book he expressed his indignation at the obsolete methods of extraction and refining. Oil was in those days being drawn from shallow wells in which there was often more brine than oil. The land in which the wells were sunk belonged to the state which leased it in lots for four-year periods. The tax-farmers, not being interested in the capital improvement of the oil-fields, handled the oil with the utmost carelessness. It was carted in leather sacks, wineskins or in barrels to the wharves and then loaded on ships. This system of leasing acted as a break on the exploitation of the oil-fields. The term of the leases was too short to allow of any returns on the investment of expensive equipment. Mendeleyev wrote sharply as he pressed for a reform of the oil industry.

"The rent system is paralysing the proper course of oil extraction and hence of the whole business," he wrote in his book. He further proposed that Baku be linked to the Black Sea by a great pipe line and that oil tankers be built. That, he argued, would enable the problem of oil transport to be effectively solved.

It was only in 1872 that the rent system in the oil-fields was abolished. When it did happen, however, the Ministry of Finance behaved as one might expect: in abolishing the rent system it placed so high a tax on oil that Russian kerosene could scarcely compete with the imported product, although it was of considerably higher quality.

But Mendeleyev's ardent statements on behalf of the development of the domestic chemical industry had their effect. His efforts joined those of the distinguished group of progressive Russian chemists with whose help Russia's chemical industry was beginning to grow.

Mendeleyev referred to his "advisory" help in the expansion of chemical production as his "third service to his Motherland."

* * *

While occupied with this work Mendeleyev continued to devote himself to the study of the principal theoretical questions of physical chemistry in which he had been interested from the beginning of his scientific career.

As we have seen, in 1865 Mendeleyev presented his thesis for the degree of Doctor of Chemistry. This thesis was on the subject of the combination of alcohol and water, being to a certain extent a continuation of his previous thesis on specific volumes. In this new work which had major significance for the elucidation of the mechanism of the process of solution itself, Mendeleyev posed questions of principle.

It had long been a matter of argument in the scientific world whether a solution was a chemical combination or a mechanical mixture of the atoms of the solvent and the solute. Proceeding from the fact that during the process of solution no law of definite proportions is observable, the majority of scientists had, on the analogy of the mixture of gases, considered solutions as a mechanical mixture. On the basis of the results of research into the solution of alcohol and water Mendeleyev put forward and defended the chemical, or, as he phrased it, the "hydrate" theory of solution. By measuring the volumes of spirit and water before solution and the volume of the aqueous solution of the spirit obtained and observing the contraction in the liquid during the process of solution, Mendeleyev concluded that contraction takes place as the result of chemical reactions between alcohol and water. In his thesis he wrote: "There is reason to believe that the fundamental law of proportions that acts not only at the moment of formation of a new established combination and also in conditions of chemical equilibrium, also operates in the formation even of such characteristic indeterminate combinations as solutions. One of the main causes of this is the long held opinion that while the process of solution is taking place the greatest change in properties is noted when we have definite proportions of the substances composing the solution." Mendeleyev went on to show that contraction of the alcohol water solution took place in conditions of the definite proportions between the quantity of alcohol and water in the solution (46 parts by weight of pure spirit to 54 parts of water).

Mendeleyev's work on his thesis did not bring to an end his studies of this highly important and interesting question. In 1887 was published the fundamental work of Mendeleyev summarizing the results of his research in the field of solutions—*Study of Aqueous Solutions by Means of Specific Gravity.*

With the publication of this work a new page in the history of the study of solutions was opened. Mendeleyev, in his own words, put forward "a conception of the nature of solutions which made them ordinary examples of chemical reactions, definite, atomic combinations similar—or perhaps identical—to combinations containing crystalline water."

"Solutions are governed by the ordinary laws of chemical action," the scientist maintained.

The study of the properties of solutions led Mendeleyev to an unexpected and, for those times, paradoxical conclusion—the properties of solutions (density, electroconductivity, etc.) change in leaps against the background of the general steady change in the proportions of the components of the solution. This conclusion Mendeleyev supported with ample factual material (he conducted experiments on the solutions of 283 substances at various temperatures and in varying degrees of concentration). This was an outstanding discovery.

As a result of changes in a solution's degree of concentration changes took place in its properties by a series of leaps. This is one of the many examples of the manifestation of a general law of transition from quantitative changes to qualitative changes. Natural materialist and dialectician as he was, Mendeleyev gave the correct physical explanation to the facts he obtained from experimentation.

Further study of the breaking points, known as "specific points," was undertaken by Mendeleyev's pupil, N. S. Kurnakov, who founded physical-chemical analysis. This new branch of chemistry allows us, by studying the relations between the composition and the properties of different systems, including solutions, to uncover their physical-chemical characteristics. This method has special significance in the study of "solid solutions" which include many alloys and other materials widely used in industry. This branch of major theoretical work, started by Mendeleyev, was also directly linked with practice; it not only influenced it but conditioned its development. For example, using the data of the physical-chemical analysis of salt solutions, N. S. Kurnakov and his school forecast theoretically and later discovered the largest deposits of potassium salts in the world, at Solikamsk.

On the other hand, the views developed by Mendeleyev were of such originality that even the most prominent chemists of those times—men like Ostwald, Arrhenius and Van't Hoff—refused to accept them, advancing against them the mechanistic theory of solutions which rejected chemism in the process of solution, i.e., the interaction of solvent and solute. Time proved the correctness of Mendeleyev's views: they acquired great significance in the chemico-physics of solutions and contributed much to the establishment of the present theory of solutions.

However, while the general picture of the process of solution given by Mendeleyev was correct, he erroneously rejected the possibility of interpreting the accompanying processes from the position of the then new views about the electrical nature of atomic interaction.

* * *

In 1867, A. A. Voskresensky's transfer to Kharkov resulted in Mendeleyev, the leading scientist in the field of chemistry, being elected to the vacant chair of inorganic chemistry at the university. For the next 23 years Mendeleyev fruitfully conducted the work of that faculty.

Mendeleyev was not only a great scientist, he was a splendid teacher, an excellent lecturer, a tutor sensitive to the needs of the student body where he enjoyed unprecedented authority and love. His lectures were full of learning and pith. Students of all faculties, even from the juridical faculty, attended them.

"Those who had the good fortune to see Mendeleyev at the rostrum," wrote V. P. Veinberg who was one of his pupils, "and to hear his lectures or reports, will remember well the particular atmosphere that reigned in the lecture-room. There at the rostrum stood a burly figure, slightly bent, with a long beard and long curly hair. The voice was deep and strong; the words tumbled out very nervously, as if Dmitry Ivanovich was groping for them. Anyone hearing him for the first time might feel a bit uncomfortable, he would want to prompt the speaker, put in a word or two. In vain! Mendeleyev always found the most expressive, unexpected words of steel-like precision. . . . His lectures delighted us with the ever-present philosophical basis of his scientific views, always visible in broad and sweeping formulas and profound analogies. . . .

"While lecturing he would often digress into mechanics, physics, astronomy, astrophysics, cosmogony, meteorology, geology, the physiology of animals and plants, agronomy and also into different branches of technology, including air navigation and artillery."

Some idea of the affection in which Mendeleyev was held by the students, and of the influence he exercised on the youth may be obtained from the memoirs of Academician A. A. Baikov:

"Long before the beginning," wrote Baikov, describing Mendeleyev's lectures, "not only No. 7 lecture-room, which Mendeleyev used, but all the adjoining premises would be packed with a lively, noisy crowd of students of all subjects who, in accordance with tradition, foregathered for the opening lecture to express their profound admiration and affection for their favourite professor, the pride of St. Petersburg University and of Russian science—Dmitry Ivanovich Mendeleyev. I, too, was among this excited, cheerful, thrilled crowd of students. We waited impatiently for Mendeleyev to arrive. In the adjacent room where the preparatory laboratory was and from where a door opened directly on to the platform we heard light steps. Dead silence fell on the lecture-room. In the door we saw the majestic figure of Mendeleyev. He was slightly bent. Long grey hair fell to his shoulders. His grey beard framed a serious-looking, thoughtful face with eyes full of concentration. What happened next I shall remember all my life. The thunder of welcoming cries and applause was enough to bring the house down: it was a storm, a hurricane. Everybody was shouting, raving, trying to give full vent to their joy, their rapture and enthusiasm.... The enthusiasm with which Mendeleyev was greeted made you feel what a great scientist, what a great man he was. He had an irresistible effect on everybody and enchanted the minds and hearts of those who had an opportunity of meeting him."

"Closely acquainted with the growth of science in his times," continued Baikov, "participating directly in the solution of the latest and most fundamental problems, being a personal acquaintance of many of the leading men of his times, Mendeleyev enlivened his exposition with personal observations and impressions."

Mendeleyev combined his intense teaching work with many public activities. These were mainly directed to strengthening and developing Russian science. St. Petersburg University, thanks mainly to Mendeleyev, became a major scientific centre. Mendeleyev secured the invitation to the chair of organic chemistry at St. Petersburg of the great Russian chemist Butlerov from Kazan; on his insistence the chair of analytical chemistry was given to N. A. Menshutkin, a distinguished scientist. Giving to the cause of teaching the best part of his life and his main forces, Mendeleyev strove to entice into science as much of Russia's talents as possible. These noble efforts had fruitful results. A large number of pupils and disciples of Mendeleyev and Butlerov continued to consolidate the high authority of Russian chemical science.

In 1868, on Mendeleyev's initiative, the Russian Physical-Chemical Society was founded. The first organizational meeting of the society took place in November that year in Mendeleyev's home and under his chairmanship. The society lost no time in expressing its gratitude to Mendeleyev and his pupil and disciple Menshutkin for their work in uniting Russian chemists.

The entire history of the Russian Chemical Society is indissolubly linked with the growth of Russian chemical science and the chemical industry. The leading scientists of Russia took part in its work: D. I. Mendeleyev, A. S. Popov, N. N. Zinin, A. M. Butlerov, N. N. Beketov, N. A. Menshutkin, A. N. Bach, N. D. Zelinsky, V. I. Vernadsky, A. E. Favorsky, V. G. Khlopin, N. S. Kurnakov, F. F. Petrushevsky, A. N. Krylov, D. S. Rozhdestvensky and other important researchers. In order to estimate the role of the society in the development of science it suffices to say that at its meetings such works as Mendeleyev's Periodic System of classifying the elements, the results of Popov's research connected with the discovery of wireless and the demonstration of the first wireless receiver in the world, and the remarkable research of Zelinsky in hydro-carbons were considered for the first time.

But Mendeleyev never forgot that his "first service to his Motherland" was his scientific work. Neither his teaching and public activities nor his concern for the development of Russian industry could tear him away from his laboratory. It was in those years of an intensive creative life that Mendeleyev reached the summit of his scientific work—he founded the Periodic System of classifying the elements.

* * *

Mendeleyev's approach to his work was always original. He never failed to add something new, something personal to whatever he undertook. As a teacher, too, his attitude was original. Taking over the course of general chemistry and starting a series of lectures the great scientist encountered a complete absence of any firm theoretical basis in chemistry. Chemistry represented a description of numerous isolated facts and phenomena. There was no clarity even at the very foundations of chemistry—the knowledge of the elements.

Despite the fact that in the 1860's the conception of the atom had become firmly established in scientific practice, few scientists saw the features of similarity between atoms of different elements, of unity in their variety. Most of them were convinced that atoms of different elements were quite disconnected particles of the universe. The study of the elements was limited to determining their properties, and describing their behaviour in this or that set of concrete circumstances.

Starting on the composition of a general manual of chemistry Mendeleyev saw that he was faced with a tremendous problem that none of his predecessors had managed to solve—the finding of a basic principle for systematizing chemical knowledge, for classifying the elements—a system based not on arbitrary, accidental and inessential indications but on such properties of the elements which are connected in the most intimate way with the nature of the atoms themselves. Among these properties Mendeleyev considered atomic weight to be one of the most important.

Mendeleyev compared atomic weight with the properties of the elements, "collecting" as he wrote, "similar elements and close atomic weights." In so doing he arrived at his brilliant discovery—which he formulated in the following words: "the properties of the elements are in periodic dependence on their atomic weights."

The Periodic Law discovered by Mendeleyev enabled scientists for the first time to generalize from known facts and to establish the connections between the elements. On the basis of this law it became possible not only to combine in a single harmonious system all the various facts that had been collected in this branch of science but also to prognosticate the existence of new elements and their properties.

Mendeleyev's *Foundations of Chemistry* was the first attempt ever made to systematize chemical knowledge with the assistance of the Periodic Law. The first edition of this capital work appeared between the years 1869 and 1871.

As far as a scientific work can do so, the *Foundations of Chemistry* provides an excellent portrait of Mendeleyev both as a scientist and a human being. "The *Foundations* is my favourite child, made after my own image; it contains my experience as a teacher and my deepest thoughts on science," wrote Mendeleyev with emotion and reverence about his work.

The scientific and technological prognostications included in the *Foundations of Chemistry* demonstrate his great confidence in the Russian people. "The time is not far off," he wrote, "when a knowledge of physics and chemistry will be considered the sign and means of education as one or two centuries ago a knowledge of the classics was." The *Foundations of Chemistry* taught the students to see in chemistry both an end and a means. Mendeleyev showed by thousands of examples how science moves industry forward and how it opens up new possibilities for using the forces of nature. The author constantly underlined in his book the importance of using scientific data for "building up the wealth" of the country.

"I believe that only by linking ideas and facts," Mendeleyev writes in his foreword to the *Foundations of Chemistry*, "by observing with well-directed thought can we act in an appropriate way; otherwise we lose sight of reality and then it is easily replaced by fiction . . . which I mean to avoid as hard as I can."

And avoid it he certainly did. Even today, when over eighty years have passed since the appearance of the first edition, this book is fundamentally up-to-date and has something of interest to every chemist who wants to broaden his scientific horizon.

Mendeleyev went on working for many years on his *Foundations of Chemistry*, constantly improving and expanding it in new editions. In 1947 the 13th edition of the *Foundations of Chemistry* appeared in the Soviet Union.

The *Foundations of Chemistry* was many times translated into foreign languages and enjoyed a well-merited popularity far beyond the frontiers of Russia. Several generations of chemists and physicists—in Russia as abroad—were brought up on this manual.

In the apt expression of Academician Baikov, the *Foundations of Chemistry* constitutes a monument which by the amplitude of its contents, the scope of its ideas, the perfection of its form and the depth of its thought is a great manifestation of human genius.

* * *

Mendeleyev was a man of inexhaustible energy. Continuing to work on his *Foundations of Chemistry* and constantly returning to the problems which the Periodic Law laid before science, he was all the time broadening the scope of his interests. And with each solution reached, science was raised to a new level. The subjects he touched were, without exception, of fundamental importance. Thus, it was not by mere chance that the study of the law of gases held his attention for a number of years.

While still at Heidelberg, Mendeleyev had carried out a number of classical studies in the field of capillatory phenomena, specific volumes and the liquefaction of gases. These he did with the single aim of "gathering material necessary for molecular mechanics."

Mendeleyev's experiments on divergences among gases to Boyle-Mariotte's and Gay-Lussac's Laws led him to discover a general equation of the state of perfect gases. In this work, which he began in 1871, he was assisted by the interest aroused in the scientific world by his experiments. The Russian Technical Society offered Mendeleyev means for organizing a laboratory for the study of the changes in the resilience of gases at different temperatures. With these means Mendeleyev equipped a laboratory at the university and set to work with his customary ardour and perseverence.

In order to elucidate the natural laws to which a substance conforms it is highly interesting to observe its behaviour at the border-line of transition from one state to another. Already in his Heidelberg experiments on liquids in capillary tubes at temperatures "when the liquid should vaporize," Mendeleyev had found the "absolute boiling point." Now he proceeded further along this fruitful path. "African explorers," he once said at a meeting of the Technical Society, "do not go to those parts of the continent that have been already opened up but try to penetrate where no foot has trodden before. So it was that I felt myself drawn most of all to that sphere of information about the resilience of gases, about which nothing, or next to nothing, was previously known. There is much unexplored territory; the important thing is to seek the most important and, at the same time, approachable things."

And Mendeleyev found these things.

In his studies of the behaviour of gases under high pressures and in a rarefied state, Mendeleyev summarized his findings in a formula which "simplified all the approximate calculations concerning gases and vapours, when the three known laws—the Boyle-Mariotte, Gay-Lussac and Avogadro's hypothesis—can be applied precisely."

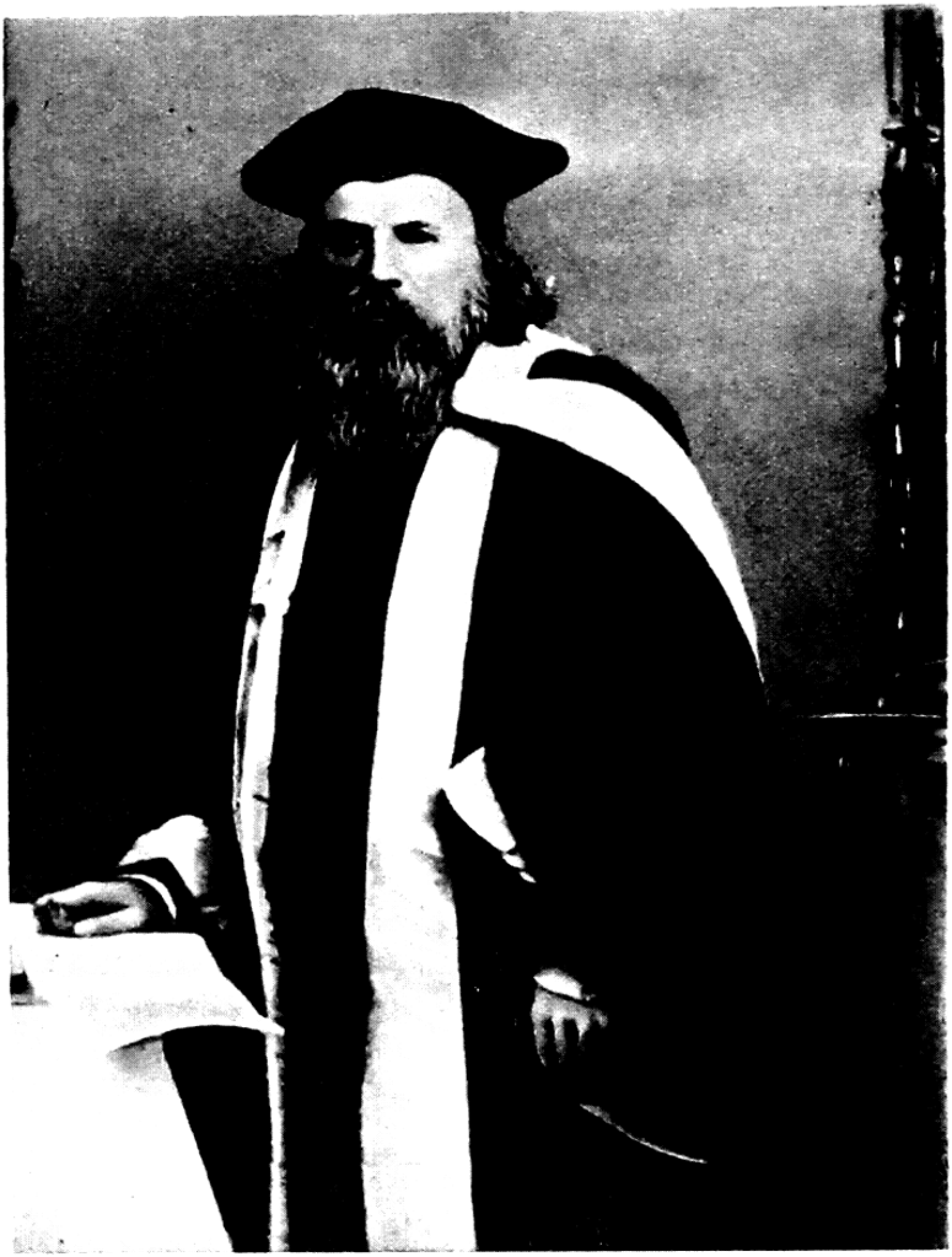
On September 12, 1874, at a meeting of the Russian Physical-Chemical Society, and five days later at a meeting of the Physics Society at St. Petersburg University, Mendeleyev read a report on his new equation of the state of perfect gases, an equation that was an improvement on the Clapeyron equation which was then accepted. As Mendeleyev wrote in his *Resilience of Gases*: "The second chapter starts with a summary of the new general formula for gases, based on the three laws pertaining to gases. The well-known Clapeyron formula is a particular case of this more general formula because, supposing the nature of a gas and its mass to be variable, my formula turns into the Clapeyron formula. By proceeding from this formula . . . I found it easy by experimental methods to analyze the possibility of error in experiments on the compressibility of gases."

Some foreign sources try to credit Herstman with this discovery but it suffices to compare the dates of the relevant published works (Mendeleyev's in 1875, Herstman's in 1881) to see the unfounded nature of this claim.

* * *

Thirty years after the death of Mendeleyev the prominent Soviet physicist S. I. Vavilov characterized Mendeleyev's activities in the following words: "Being by training a chemist and working on chemical material,

A group of members of the Russian Physical-Chemical Society (1868). Mendeleyev—second from right in second row



Mendeleyev in the gown of an honorary graduate of Oxford University (1894)

Mendeleyev always approached his subject with the broad point of view of a physicist and considered chemical processes and states as the still-unsolved tasks of physics. In the field of chemistry Mendeleyev was a physicist, while in physics his main interest—one might saw his exclusive interest—was in chemical problems. Mendeleyev could hardly be described as a physical chemist in the generally accepted, old sense of the phrase; he was certainly far closer to the branch of science which we have recently come to call chemical physics, the characteristic of which is—at least in principle—the attempt to treat the whole field of chemistry as a special problem of physics."

As always, Mendeleyev's main work was supplemented by other researches. Mendeleyev did not dissipate his energies, he simply found time for everything. Looking back over his life in his old age he wrote with pride: "I am myself surprised at the amount I managed to do in my scientific career." While studying the behaviour of gases he carried out research into meteorological phenomena, worked on the Russian oil industry, travelled abroad, campaigned against spiritualism, etc., etc.

Mendeleyev was never interested in science purely for the sake of science. Even in his most abstract, purely theoretical works he knew how to stress what was important for practice. That is why his work on gases was closely linked with his keen interest in meteorology. Of that he wrote himself: "While busy with questions about rarefied gases I willy-nilly entered a sphere that is close to the meteorology of the upper strata of the atmosphere. So little attention, indeed, has been given to this question that it seemed to be sufficiently important to receive general attention, especially in the light of the fact that in the atmospheric strata considerably removed from the Earth a search should be made for a region where most of the meteorological conditions occurring on the surface of the world are formed."

"We were not the first to understand the necessity and usefulness of this study of the atmosphere," he continued. "It was in Lomonosov's mind before others. . . . We must study the climate at various atmospheric levels and in various continents. Russia, because of its great land mass, is more suitable than any other country. . . . Here we have a weather laboratory, here clouds are formed, here they move, and yet here we rarely find any measuring instruments. There is interest in the question, the necessity is clear, we can find the forces—but we need means. Surely they will be forthcoming!"

Mendeleyev did not wait for the state to allocate the necessary funds; he realized this might take a long time. In all his published works relating to that period we find the same words: "The receipts from the sale of this work are being donated by the author for the construction of a large aerostat and for the study of meteorological conditions in the upper atmospheric strata."

Mendeleyev's aim was to observe the "weather laboratory." And, as was always the case, his aim and actions coincided. He designed a number of instruments for carrying out scientific investigations in the upper atmosphere. In his article "The Levelling of Barometres and Height Measurements" published in 1876 in the *Inzhenerny Vestnik* (*Engineering News*) Mendeleyev describes a highly sensitive differential barometer—a height-indicator of his own design. With the help of this instrument the height above sea-level can be established with great speed and accuracy. Later, other instruments based on his principle were widely used.

At a meeting of the Russian Physical-Chemical Society, Mendeleyev delivered a report on his plan for building an aerostat with a hermetically-sealed gondola in which the pilot would be "provided with compressed air" and could "make observations and steer the balloon in safety." The construction of a gondola of this type was a complicated task; it could, however, be simplified and in some cases the observer could be replaced by automatic recording instruments. Mendeleyev gave a description of one possible version of such instruments. "The instrument designed by D. I. Mendeleyev," we read in the Society's minutes, "offers the possibility of carrying out observations in the atmosphere without the presence of an observer."

Mendeleyev of course could not turn down the invitation to take part in the balloon ascent into the "weather laboratory," although the purpose of this ascent was somewhat different—the observation of the solar eclipse of August 7, 1887. Mendeleyev described this memorable ascent in his article "Balloon Ascent at Klin."

According to the original plan, Mendeleyev should have made this ascent with the experienced airman Kovanko, but at the last moment it appeared that the balloon had not the lift to take two passengers and Mendeleyev decided to go alone.

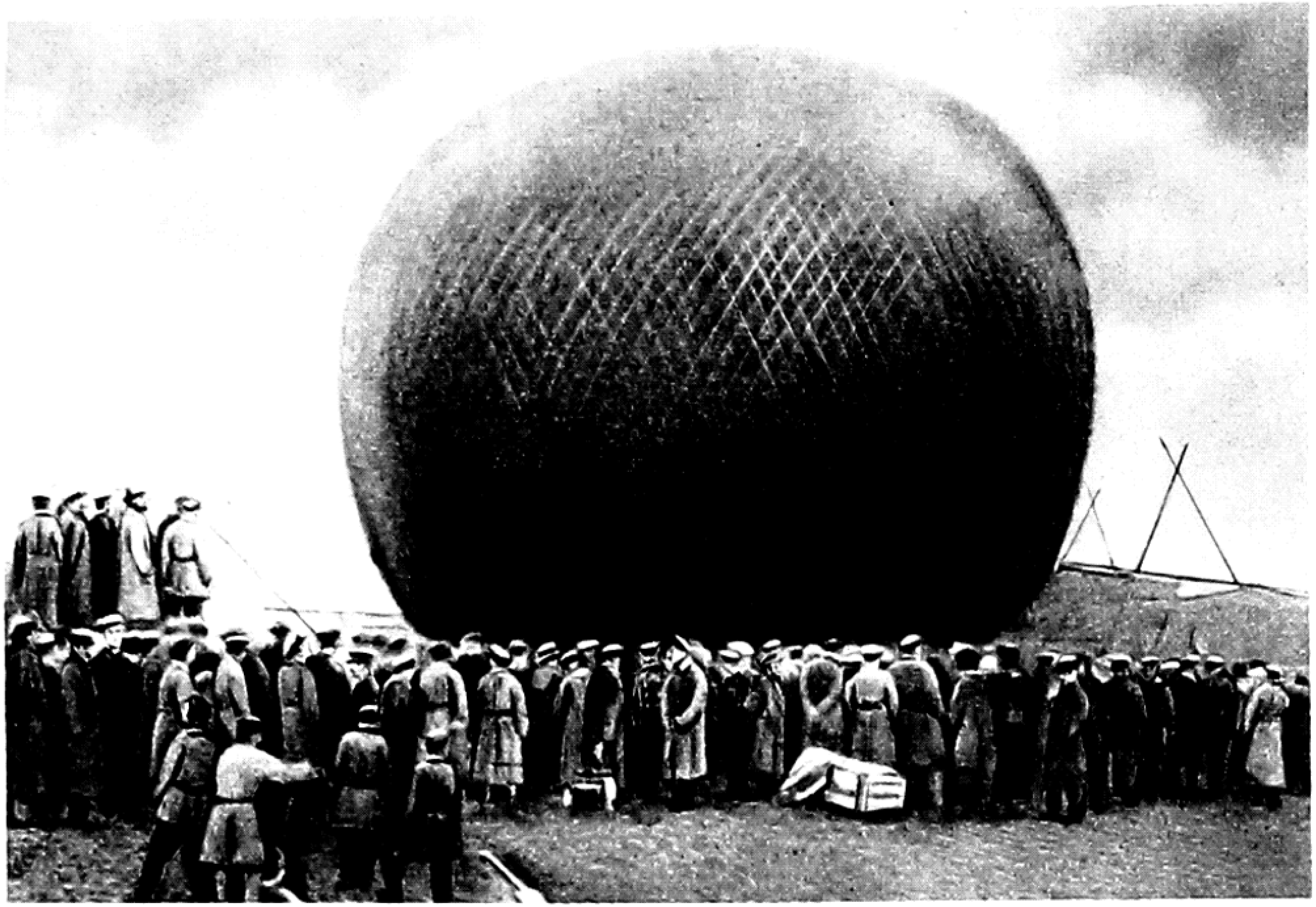
"An aerostat is also a physical instrument," he firmly told his friends when they tried to dissuade him from going. "You can see how many people regard this ascent as a scientific experiment. I cannot destroy their faith in science." In these words is contained all Mendeleyev's own ardent faith in science, his feelings of responsibility towards the public for the cause of science.

Mendeleyev carried out this risky solo flight safely. In a newspaper article about it he described in detail his observations and impressions. His niece N. Y. Kapustina, who watched the ascent, wrote about Mendeleyev's landing at Klin: "...the local inhabitants gave Dmitry Ivanovich an ovation at the station and in the streets when he came and wanted to unharness the horses so that they could draw the carriage themselves, but he did not allow them to do that."

* * *

Since 1864, Mendeleyev, himself the leading technical chemist of Russia, had held the chair of industrial chemistry at St. Petersburg Technological Institute. His remarkable capacity for knowing how to find the grain of living practice in every scientific problem—even in the most abstract of them—manifested itself to an outstanding degree in the development of Russian industry. He had been interested in technological questions since the very beginning of his scientific life. "I grew up near a glass works," he wrote. "My mother was its manager, supporting the children she had been left with. Since childhood I knew what factory work meant and grew used to the idea that the factory is one of the nation's breadwinners, even out there in Siberia; that is why, while devoting myself to such an abstract and real science as chemistry, I was interested from early days in factories and workshops." As we have seen, this interest was not the idle whim of a theoretician but took the form of active participation in all industrial matters; it was the ardent, keen activity of a man who took a vital interest in the prosperity of his native land.

Since his visit to Baku, Mendeleyev had never ceased to be interested in the development of the oil industry. We have already mentioned that he campaigned energetically against the rent system of the oil-fields. When, in 1872, the Ministry of Finance imposed a high tax on refined oil, Mendeleyev was no less active in his opposition to this new hindrance to the expansion of the oil industry. He also advocated the removal of the tax on salt, needed by the chemical industry. The oil tax hindered the introduction of new advanced methods into the working-up of oil. For instance, the tax was reckoned not according to the production of plant installed but on the basis of the capacity of the refineries and the time taken in the process. In fact, the tax collectors prevented the introduction of new methods of continuous refining proposed by Mendeleyev. With the support of the Russian Technical



Before Mendeleyev's balloon ascent (1887)

Mendeleyev and his fellow travellers during his Urals expedition (1899)

Society, Mendeleyev tried to convince the Ministry of Finance that the removal of the tax would allow the oil industry to expand and hence, bring in a substantially greater revenue to the treasury, more than enough to compensate for the removal of the tax. To gather material to support his point of view Mendeleyev visited, in 1876, the American oil-fields. His book *The Oil Industry in the North American State of Pennsylvania and in the Caucasus* contains a grim picture of conditions in capitalist America.

Mendeleyev found America in the throes of an industrial slump which brought out clearly and precisely all the negative aspects of capitalism. In striking terms he noted and described the poverty-stricken lives of the workers, their lack of rights, the cut-throat competition between the proprietors and the discrepancy between the level of the oil extraction and the real possibilities of the industry. Describing the wretched, crudely-built shacks that housed the equipment, the squalid barracks for the workers and the clumsily-built timber derricks, he concluded: "The business is obviously being carried on with no other concern but commercial profit." He did not find the slightest trace of mechanization in the oil-boring. A growing army of unemployed workers besieged the Pennsylvanian oil-fields. "In the installation of machinery to replace manual labour," wrote Mendeleyev, "I could see no desire to ease the workers' heavy lot, no desire for improvement in performance, for I noticed that most of those who handled machinery had to do a tremendous amount of work and the greatest attention was demanded from them, while children were put to work on machines that did not need much looking after." The oil-refining was also on a low level: "There was not a trace of research, attention or desire for improvement in the refining." The inefficient refinery equipment simply devoured fuel. Mendeleyev explained this by the fact that "profit was the only objective."

These observations were evidence of great foresight. Since those days the American oil industry has made great advances but at the same time the contradictions in capitalist society have deepened. Ideologists of the capitalist system try to present technical progress as the inevitable consequence of the "civilizing role" of capitalism. We know that in fact the only motive force in capitalist society is the desire to gain profit at any cost, including the merciless exploitation of the workers, and, if profitable, the rejection of modern machinery.

In conclusion of his American impressions Mendeleyev wrote: "It was clear that in the North American states it is not the best but the average and worse than average sides of European civilization that found expression and development. . . . The new dawn is not to be seen on that side of the ocean."

On his return to Russia, Mendeleyev campaigned still more energetically for the development of a domestic oil industry. In 1876 the oil tax was removed. Mendeleyev, however, was not satisfied. He went on insistently airing the idea of chemical refining methods for oil. "This is a most precious material," he urged, "it must be worked up into other very important products, not only as fuel. Otherwise we are just burning money!"

In the interests of expanding the oil-refining industry Mendeleyev invented a "new method of fractional refining suitable for the extraction of the light parts of Baku oil." He tested in factory conditions new methods of oil-refining and a new refining apparatus with his own improvements. He was also highly interested in the thermal treatment of oil—the future cracking method.

Mendeleyev proved the great usefulness of founding a ramified oil-refining industry with installations located along the main water-ways. In a dispute with the important Nobel Brothers Oil Company he demonstrated the benefits that this plan would bring to the national economy, and wrote: "The question is not the cost of refining;

what matters is the advantage brought by the works and the trade, by a large national undertaking and the expansion of extraction, by the cheapening of the products and the improvement of their qualities."

Mendeleyev's works played a vast role in the development of Russia's oil industry but it was only in conditions of planned socialist economy that his progressive ideas on the decentralization of extraction and refining of oil were put into practice.

The creative ideas of the great Russian scientist penetrated almost every important branch of industry. At a congress of Russian natural scientists and physicians, held in December 1879, Mendeleyev spoke about the role of natural science as an auxiliary to industry. His speech received an ovation. Looking into the future Mendeleyev said: "Natural science, which was established in Russia so recently, is growing mature. In his youth a man is apt to think only about the interests of his head and his heart, but when he grows up it is fitting that he remember real practical necessities. That is why it is high time we gave some thought to meeting the needs of this country in which we live and grow. Working for the benefit of world science we, of course, pay tribute to our Motherland. But surely Russia has its own local requirements, among which are those which we, more easily and conveniently than anyone else, can satisfy, since they are closer to our ken and reach. Let us realize this so that no one will be able to say that we gathered to study world scientific interests but neglected the familiar close-at-hand questions of immediate benefit to our country. . . ."

"Natural scientists!" he appealed to them. "Let us describe in the simplest language . . . Russia, its climate, its soil, its vegetation, its fauna and peoples; let us point out its mountains and rivers, its forests and deserts, the whole aggregate of conditions that have significance for the economic life in those outlying parts of Russia where it may still be possible to settle large numbers of people —if not now, then in the future."

Mendeleyev himself did much to implement this broad programme.

He was the founder of Russian agrochemistry. In his works in this field he strongly opposed the widely held "theory" of the exhaustion of soil fertility. In contrast to this, "Malthusian gibberish," Mendeleyev maintained that it was possible to increase the productivity of agriculture many times over.

In 1866 Mendeleyev offered to draw up the scientific principles for a Russian school of agronomy, using methods of exact sciences. In three years he succeeded in carrying out in field conditions experiments on the study of deep ploughing and the action of fertilizers in the Smolensk, St. Petersburg, Moscow and Simbirsk gubernias. This was "an experimental field system"—as K. A. Timiryazev, himself an active participant in the experiments, wrote of Mendeleyev's work—"the very first ever to exist in Russia." With precise experiments Mendeleyev proved that mineral fertilizers, which at that time were just being introduced into general farming practice in some West-European countries, could in suitable conditions become an effective means of increasing Russia's harvest. One of the most important results of the Mendeleyev experiments was the discovery and vindication of the beneficial influence of lime on crops in *podzol* soil.

In 1888, at the invitation of the Ministry of State Property, Mendeleyev went to the Donets Basin to conduct research into the possibilities of developing the coal-mining industry. His report on this journey was published in 1888 in the *Severny Vestnik* (*Northern News*) in the form of an article entitled "Future Power Lying on the Banks of the Donets." In this work Mendeleyev not only gave a detailed description of the prospects for exploiting the wealth of the Donbas but advanced the idea of underground gasification of coal, going far beyond the limits of practical possibilities in those days. "There will be a time," he wrote, "when coal will not be extracted from the earth but will be converted underground into combustible gases which will be distributed over vast areas through pipes."

The idea of underground gasification, which Mendeleyev developed in more detail in 1899, was taken up by the well-known Scottish chemist William Ramsay. In 1913, Lenin, in an article "One of the Great Victories of Technique" wrote that the realization of this idea "means a gigantic technical revolution."

Reflections on the development of the Donets mining region naturally led Mendeleyev to the idea of canal construction along the course of the Donets and its tributaries and of connecting the coal-fields with centres of the iron industry by water. He drew up a detailed plan for transforming the Donets into a broad navigable river. . . . At the same time he admitted that his dreams were purely utopian. "In speaking all my mind about the Donets," he wrote bitterly, "I am above all afraid that little interest will be taken in the course of action that I propose. But if I had started talking about a project that would cost millions, specially if there were concessions in it, then I would have been accused of having my eye on those millions, others would have managed to get their teeth into them and there would have been a lot of noise, argument and interest."

In 1899 Mendeleyev undertook another long journey, this time to the Urals. He was in poor health but made this tiring journey with the single aim of helping Russian industry—"to find out on the spot where the reasons lay for the stagnation of the Urals iron industry." In his books *Towards a Knowledge of Russia* and *The Urals Iron Industry in 1899* Mendeleyev came to the conclusion that what was retarding the industrial development of the Urals was the interests of "rich men living elsewhere than in the Urals"—the monopolist owners who were always ready to strike up on the basis of the general struggle for super-profits. "The old works keep going, they operate, but 'slowly' for the simple reason that nobody and nothing pushes them ahead, while any competitor who comes along finds all roads closed, and is told flatly to go elsewhere; we get along more quietly without you and the system of protection provides us with a profit even in our 'slow-motion.' "

To wreck the plans of a few owners of the wealth of the Urals to establish their monopoly there, Mendeleyev advised the authorities to sell ore at fixed prices to all comers, and thus to maintain an average price for the raw material.

A true scientific analysis of the situation in the Urals before the Revolution was made by Lenin in his classic work *The Development of Capitalism in Russia.*

". . . The most direct remnants of the pre-reform order, a highly developed system of *otrabotki*, the bondage of workmen, low labour productivity, backward technique, low wages, prevalence of manual production, primitive and rapaciously primaeval exploitation of the natural resources of the region, monopolies, impeded competition, isolation and detachment from the general commercial and industrial trend of the time—such was the general picture of the Urals."

During his trip to the Urals Mendeleyev saw the great riches of that region that lay under its superficial aspect of poverty. He returned to St. Petersburg firmly convinced of the future prosperity of the Urals. He wrote with enthusiasm: "When I left for the Urals, I knew, of course, that I was going to a region rich in iron and capable of providing Russia's needs. When I travelled through the region and saw its wealth of iron, timber and coal not only with my own eyes but through those of my three travelling companions, I was convinced in a way that surprised me that when we have carried out a few not very costly measures which, in any case, will be quite profitable to the state, the Urals will provide Europe and Asia with huge quantities of iron and steel at a production cost which would be quite inconceivable in Western Europe. This convinction compensates a hundred-fold for the difficulties of the journey and allows me to turn with an easy mind to other matters on my programme. My faith in the future of Russia, which was always alive in my heart, has matured and strengthened as a result of getting to know the Urals."

It was during his visit to the Urals that Mendeleyev pursued further his previous idea of the underground gasification of coal. Observing underground fires in the Kizelovski district he decided that it was possible to control them. "In connection with this loss of coal seams," he wrote in his report, "it seems to me that the conflagrations could be used by being put under control in the way a generator works, i.e., by small inlets of air. . . . It would be specially valuable to start our experiments with an attempt to convert into combustible gases underground those narrow seams—less than an *arshin* (28 inches) thick—which are not usually exploited."

In his mind's eye Mendeleyev saw the mouth of the Donets widened, the transport of raw materials and goods planned, the production of pig-iron and steel in the Urals put on a proper footing, and industry run by the public in a co-ordinated way. Naturalist, chemist, technologist, economist, Mendeleyev cherished these thoughts because he stood on the firm ground of objective reality, submitted to the logic of its requirements. He was close to an understanding of those premises which lay at the foundation of the well-known statement of Lenin: "Wherever you cast your glance, at every step you encounter tasks that mankind is perfectly able to carry out *at once*. But capitalism stands in the way." Mendeleyev could not form so natural and decisive an opinion as this. He was still far from scientific socialism.

Mendeleyev's tireless activities are difficult to describe in the narrow frame of an essay. Inevitably, many events have to be passed over, the chronological order of others broken. We are dealing with a giant in thought and deed, one who did so much in his time. His whole life was devoted to serving his people. His remarkable words are fully applicable to himself: "The greater a man's natural gifts, the greater his responsibility to society." With all his mighty talent as a scientific publicist, Mendeleyev glorified the great transforming power of labour. But he stopped half-way. He saw so many contradictions in the society he lived in, yet he believed that in the framework of that society it was possible to achieve a unity of science, industry and labour. He could not understand that only in conditions of emancipated labour could there be achieved that flourishing of science and industry of which he dreamed so much and which he called for with so much passion and conviction.

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During the 1870's Mendeleyev's private life underwent some important changes.

In 1862 he had married Feozva Nikitichna Leshcheva, a narrow-minded, neurotic woman of poor health whose interests were confined to the family circle. Even before he had grown to know his future wife at all well, Mendeleyev wrote to his sister Olga Basargina—in whose house he first met her—that the better he knew his betrothed the clearer he saw that his feelings for her were not those that a fiancé's should be. His sister, however, reprimanded him sharply. "Remember what the great Goethe said: 'there is no sin greater than betraying a maiden's trust.' You are engaged, the betrothal has been announced; what sort of position will she be in if you throw her over now?" Mendeleyev submitted, and, in 1862, the marriage took place. As could be imagined, it turned out to be an unhappy one. Mendeleyev looked to his wife for an understanding of his calling, for her comradely support. But in fact he was alone in his great work, and felt this loneliness keenly.

Discord arose, the result not so much of personal incompatibility between the two as of Mendeleyev's conflict with the whole patriarchal world which surrounded him.

In 1876, in the home of another of his sisters, E. I. Kapustina, Mendeleyev made the acquaintance of a highly intelligent and artistically gifted friend of his niece called Anna Ivanovna Popova. He fell in love with her. Divorce, however, was far from easy to obtain. It was four years before his wife's reluctant consent could be obtained. In 1880 Mendeleyev remarried.

From then on, his home was no longer the quiet place it had been during his first marriage. At first every Friday, and then on Wednesdays the leading figures in Russian art and science met there. Among the regular visitors to the Mendeleyevs were Kramskoi, Repin, Yaroshenko, Myasoyedov, Kuinji, Vasnetsov, Surikov, Shishkin and other artists in the Peredvizhniki group*.

Wednesdays at the Mendeleyevs were always lively affairs. In her memoirs, Anna Mendeleyev writes: "These Wednesdays were very popular among artists. They provided neutral ground where people belonging to different camps could meet. The presence of Dmitry Ivanovich had a moderating influence on extremists. Here one got all the latest news of the art world. The galleries used to send their art publications for scrutiny at our Wednesdays. Sometimes pioneers in various fields of art brought their inventions and demonstrated them. It was a Wednesday evening party that F. F. Petrushevsky got the idea of writing his book on paints.... The atmosphere that Dmitry Ivanovich created wherever he appeared, high intellectual level, lack of interest in petty affairs and gossip made these Wednesdays singularly interesting and pleasant."

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* Russian realist painters belonging to the Society of Travelling Art Exhibitions. They opposed the reactionary style of the court-patronized Academy of Art, which was far from life.

Mendeleyev became passionately interested in painting. When Kuinji exhibited his picture *Night on the Dnieper*, which is now to be seen in the Tretyakov Art Gallery in Moscow, Mendeleyev wrote about it an article which he called "Before a Picture by Kuinji." This article contained many profound ideas on art.

As a recognition of Mendeleyev's great interest in painting and a tribute to his understanding of art, Russia's painters in 1894 elected Mendeleyev to membership of the Academy of Arts.

The Peredvizhniki movement in art, the Mighty Five* in music with which Mendeleyev had connections through the chemist and composer, Borodin, his friend of Heidelberg days, and the new upsurge in science in which Mendeleyev was so active a participant—these were different aspects of the general cultural upheaval and the flowering of social thought in the sixties and seventies, connected with the abolition of serfdom and the growth of the democratic movement in Russia.

Mendeleyev's chief love and principal interest, however, remained his scientific work. Few were the hours he could spend with his family. From early morning he was at his desk, and, if the day was free from lectures, he would remain there until half-past five without a break. According to established tradition he would dine at six. After dinner it was his custom to work again until late at night. Thus his life flowed on from day to day, a life filled to overflowing with the painstaking, creative work he loved so much.

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* The name given to a group of composers in the 1860's who came out against the survivals of serfdom and upheld the principles of democratic art.

In the history of world science the names of but few scientists are to be found linked with such great discoveries as Mendeleyev's is. All the more deplorable were the events that occurred in the Russian Academy of Science in 1880.

According to its charter the Academy of Science was the "leading scientific estate in the Russian empire." The charter laid down that "the Academy enjoys the right to elect as vacancies occurred academicians and junior academicians"—scientists who by their works "are endeavouring to broaden the frontiers of any branch of knowledge useful to mankind and to improve and enrich it by their discoveries . . . the Russian scientist to be preferred to the foreign one in cases where their achievements are identical." That was how the words ran; in practice, however, it was a different story.

After the death of N. N. Zinin, Academicians Butlerov, Chebyshev, Ovsiannikov and Koksharov put forward as candidate for the Academy's vacant chair of chemical technology the name of D. I. Mendeleyev "whose right to a seat in the Russian Academy of Science, no one, of course, will dare to dispute." There seemed to be no grounds for doubting that Mendeleyev would receive the post. There was no one with claims to equal his, not only in Russia, but anywhere in the world.

On November 11, 1880 a ballot was held on Mendeleyev's candidateship at a meeting of the physical-mathematical section of the Academy of Science. The reactionary majority in the Academy again showed its hand. Mendeleyev failed to obtain the necessary support. He shared the fate of many distinguished Russian scientists, the victims of the desire of tsarist reaction to stifle all that was alive and creative in Russian science.

When the news became known that Mendeleyev had not been elected to the Academy, a wave of indignant protest swept through scientific circles throughout Russia.

The Moscow professors wrote to Mendeleyev: "For those who have followed the activities of the institution which by its charter should be the 'leading scientific estate' in Russia, the news came not altogether as a surprise. The history of many academic elections has clearly shown that in that institution the voices of men of science are being suppressed by the opposition of dark forces which are jealously shutting the doors of the Academy to Russian talent."

Scientific and progressive opinion in Russia thoroughly understood that Mendeleyev had been kept out of the Academy as the result of reactionary pressure. As a mark of protest Kiev University set the example to all the other universities of Russia by conferring an honorary degree on the great scientist. Truly may it be said that Mendeleyev was elected by all scientific and progressive Russia into the "leading scientific estate."

When Mendeleyev learned of the action taken by Kiev University he wrote to the Rector: "I thank you and the Kiev University Council most heartily. I realize that what is concerned is the Russian name, not me personally. What is sown on the field of science will ripen for the people to use."

The reactionary element in the Russian Academy of Science was not able to diminish the glow of world fame that Mendeleyev enjoyed. At that period the world's most ancient universities, including Cambridge and Oxford had conferred degrees on him. Famous academies such as those of London, Rome, Paris, Berlin, Boston, and over fifty different scientific associations in Russia, Western Europe and America had elected him to membership.

The "Mendeleyev affair" was much written about in the progressive press of those days. A. M. Butlerov's sharp article "The Imperial Academy of Science—Russia's or the Emperor's Only?" that appeared in the newspaper *Russ* resounded all over Russia. In that article with an exceptionally bold title the great Russian organic chemist protested against the attempt to elect a mediocre

German professor F. F. Beilstein to the very chair of chemical technology for which Mendeleyev's candidature had been rejected.

The "Mendeleyev affair" left a strong and ineffaceable imprint on Russian public opinion. It exposed to the general public the shameful position taken up by reactionaries and served as a cogent appeal for struggle for a free Russian science which would serve the interests of the people honourably and selflessly.

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After the assassination of Alexander II by Russian revolutionaries in March 1881, reaction launched its offensive. An era of social stagnation set in. The authorities made every effort to root out the "nihilism" which, it was claimed, had penetrated science. Mendeleyev had to suffer much as the result of this policy, which reflected a serf-owning mentality and made itself felt with blunt directness in all spheres of public and state life. But the cruelest blow he had to bear came in 1890 when after thirty-three years of work there the scientist was obliged to leave St. Petersburg University.

The direct cause of Mendeleyev's break with the university was his conflict with the Minister of Education, Count Delyanov. Academician Baikov describes what happened in the following words:

"In March 1890, student disturbances started in St. Petersburg University. They attained a large scale. The students organized meetings to discuss their demands on the government and drew up a petition; when everything was ready they invited the teaching staff to a meeting. Among those who attended was D. I. Mendeleyev who was immensely popular among the students. They loved him, admired him tremendously. The question arose of presenting the petition that had been drawn up to the government. Mendeleyev was invited to do it. He accepted, and promised to deliver the petition. . . . This happened during a period of the darkest obscurantism, the reign of Alexander III, when everything alive was stifled, suppressed and persecuted. So it was no simple and easy matter for Mendeleyev to assume such a responsibility and mission. In this Mendeleyev showed his greatness not only as a scientist but as a man, as a citizen.

"Well do I remember the lecture at which Mendeleyev accepted the petition. It was March 14, 1890. An enormous number of students had gathered for that half-lecture, half-meeting. When Mendeleyev arrived he was met with thunderous cheers, applause and other expressions of admiration. . . . On March 16, Mendeleyev presented the petition to Delyanov who returned it to him with the minute: 'On the instructions of the Minister of Education the enclosed document is returned to Councillor of State Professor Mendeleyev since neither the Minister nor anyone else in the service of His Imperial Majesty has the right to accept a document of this nature. To His Excellency D. I. Mendeleyev, March 16, 1890.' "

Considering that it was impossible after this incident for him to remain at the university, Mendeleyev submitted his resignation and, in the summer, moved from his rooms in the university to a new apartment.

The news of the minister's rejection of the petition and of Mendeleyev's resignation caused further outbreaks in the university. The university authorities called in the police; many arrests were made, the protest was suppressed. It was in these circumstances that Mendeleyev delivered his last lecture—on March 22, 1890. . . . Its closing words ran: "Pray do not, for a variety of reasons, applaud when I leave the hall." So impressed was everybody by these words that there was not a word spoken, not a sound of applause, as, in dead silence, Mendeleyev left the lecture-hall for good.

Mendeleyev deeply felt his departure from the university. His thirty-three years of work had required a tremendous expense of spirit, passionate, ardent work. And was this to be his only reward? His finest thoughts and aspirations were bound up with the university. The scientist was forced in his old age to quit his laboratory, his pupils. Mendeleyev felt so deeply offended that for a time he remained confined to his quarters and refused to receive anyone.

But Mendeleyev was not the kind of man to be inactive for long. His dynamic energy, his love for his country made insistent calls on him. The government's attitude remained callous. For Russia—for the Russian people—he had always been, and would continue to be one of the nation's finest, most beloved sons. The government was not Russia, that Mendeleyev realized. No, he would not emigrate, he would stay in Russia. In disgrace, maybe. As a former professor of St. Petersburg University. But he would go on working for the benefit of his native land.

In the spring of 1890, the Admiralty, and, later, the Ministry of War, invited Mendeleyev to work on the production of a new type of smokeless gunpowder.

Mendeleyev attached the greatest importance to the establishment of a domestic source of smokeless gunpowder. In a memorandum to the Ministry of War he wrote: "Laboratories for explosives should be considered as a long-sighted weapon of war since explosives have brought about a real revolution in the armed forces of all lands. Russia must be placed on a firm footing in this respect."

Struggling, as always, against stagnation in the development of Russian industry Mendeleyev sought to convince the Ministry of War that "the supply of the Russian armed forces with smokeless gunpowder is one of the largest industrial undertakings in the world." He insisted that concessions for the production of new types of gunpowder be granted only on conditions "that the sulphuric acid should be obtained from Russian pyrites"—that domestic raw materials be used.

During 1890 and 1891 Mendeleyev evolved a new kind of gunpowder. "This type of collodion," he wrote in this connection, "ought to be considered a new and hitherto unapplied form of nitrocellulose, something between the usual pyroxyline, containing about 13% nitrogen and chemist's collodion which is used for treating light wounds, with about 11% nitrogen." Hence Mendeleyev gave the name of pyrrocollodion to this form of nitrocellulose.

Pyrrocollodion gunpowder was given its first firing tests in 1892. The results were brilliant. Mendeleyev's gunpowder proved to be superior to foreign makes on the score of speed and evenness of combustion. In the summer of 1893 its suitability for naval artillery of all calibres, including the largest, the 12-inch gun, was established. Following these successful tests the new gunpowder was put into factory production.

But in 1894 Mendeleyev was obliged to leave the Admiralty—"on account of the unfriendly, I should say, hostile attitude on the part of certain influential persons in the naval artillery"—recalls S. N. Vukolov, Mendeleyev's assistant in the Naval scientific-technical laboratory, organized in 1891, where Mendeleyev conducted his work on gunpowder. This was another blow at Mendeleyev from the part of the ruling clique of the military bureaucracy.

Mendeleyev's departure had grave results for the development of gunpowder production in Russia. Some strong hand was able to cause a contraction in the production of pyrrocollodion powder in Russia. And during the First World War Russia had to order urgently several thousand tons of smokeless pyrrocollodion gunpowder from the United States.

* * *

In Mendeleyev's old age his name was closely associated with the development of Russian metrology, the science of measures and precise measuring.

In the year 1892 Mendeleyev was offered the post of scientific treasurer of the Office of Standard Weights and Measures. Realizing the importance of developing the technique of measurement in connection with the increased demand for it in science and industry, Mendeleyev accepted the post.

His arrival at the Office of Standard Weights and Measures was marked by a fundamental reorganization of this institution. In 1893, according to Mendeleyev's plans, it was transformed into the Main Chamber of Weights and Measures. Mendeleyev himself was placed in charge. In a short time he turned it into a first-class scientific research institute. In order to carry out work on the re-establishment of the main units of measurement Mendeleyev created for the first time in Russia an extensive range of special laboratories—weighing, thermometric, electrical, photometric, hydrometric, gasometric, etc.

Mendeleyev's brilliance as an experimenter and his understanding of the great importance of a precise knowledge of units of measurement for measuring work caused him to start his activities in the Main Chamber of Weights and Measures by overhauling and putting in good order the fundamental prototypes of weights and measures—the *arshin* and the Russian pound. This was a big and exacting task. To fulfil it Mendeleyev specially worked out the theoretical basis of methods of precise measurement. Over twenty thousand separate weighings had to be made in order to establish the exact weight of the prototypes of the Russian pound, the *lot* (about half-ounce) and the *zolotnik* (4.35 grams) and to make facsimilies of these prototypes. The research work carried out enabled the mass of the pound to be established to the sixth decimal point—a hitherto unknown degree of accuracy, being two points further than previous researchers had reached either in Western Europe or in Russia.

"The degree of accuracy arrived at in the Main Chamber of Weights and Measures is higher than that attained in Britain or France," wrote Mendeleyev.

In six years—a record short time for those days—Mendeleyev completed the entire work. Prototypes of the weights and measures were produced. In other metrological institutes work of this nature took from 15 to 20 years.

Mendeleyev's work in metrology won universal renown and together with the work of his followers raised Russian metrology to the first place in the world.

In 1899 Mendeleyev succeeded in introducing the metric system though it was not at that time obligatory in Russia.

On his initiative in the following year, metrological laboratories (control chambers) were set up all over Russia; under the control of the Main Chamber of Weights and Measures, they began to put into practice methods of precise measurement. And when on September 14, 1918 the Council of People's Commissars decreed the introduction of the metric system, the country, thanks to Mendeleyev, was ready for it.

* * *

... The years pass, years full of selfless creative work. Old age crept on Mendeleyev all but unnoticed. Much, very much was achieved. But there remained so much undone, so much that he wanted to do.... His life had been full of events, he had much to tell, "for it is bursting to be told and I do not wish to commit the sin of keeping silent; I must write my *Legacy of Thoughts*. Will I have enough time to do it, and have I the power? ..."

Mendeleyev wasted no time. The motto of his whole life was work: "Work; look for peace and calm in work, you will find it nowhere else! Pleasures flit by—they are only for yourself; work leaves a mark of long-lasting joy, work is for others." And Mendeleyev himself, the tireless worker, worked till the last day of his life. In his swan song—*Legacy of Thoughts*—he intended to provide as full as possible an account of his scientific and pedagogic views, his opinions on Russia's industry and social events.

His sight began to fail, but still he went on working: ailing, half-blind, he dictated his *Legacy of Thoughts* to his secretary.

Early in January 1907, at the Chamber of Weights and Measures, Mendeleyev received the newly appointed Minister of Trade and Industry, Filosofov. He personally acquainted the minister with all the work that the Chamber carried out. In seeing the minister to his carriage Mendeleyev caught a chill in the cold wind. It proved fatal.

In the memoirs of N. Y. Kapustina-Gubkina, a relative of Mendeleyev's, an account appears of the last hours of the life of the great Russian scientist. The story tells of his sister's last visit to him shortly before his death.

"She came into his study where he sat looking pale and with a strange expression on his face. He held a pen in his hand.

" 'What's the matter, are you feeling ill, dear? You'd better lie down,' she said.

" 'No, it's nothing.... Have a cigarette, Mashenka,' and he offered her cigarettes.

" 'I'm afraid it will be bad for you if I smoke here.'

" 'Oh no, I'll have a cigarette myself...' and he lighted one. And his pen was in his hand. She came in again to him later and saw that he was hardly able to sit up. But the pen was still in his hand...."

Mendeleyev died of heart failure at five o'clock in the morning of January 20, 1907.

There were great crowds following the bier when, on a frosty day, Mendeleyev's body was borne to the Volkovo cemetery. The street lamps, draped in black crepe, burned wanly in the daylight. St. Petersburg was according its last honours to a great Russian.

The year Mendeleyev died N. A. Morozov, the distinguished scientist and revolutionary, wrote: "Newton and Kepler, Darwin and Marx, and with them Mendeleyev, are dear to all thinking humanity because of their theories. Their discoveries lie at the basis of the outlook of each one of us and will continue to serve future generations in the same way. That is why not only men of science and student youth but the representatives of all manner of branches of work followed the coffin of Mendeleyev when on January 27, 1907, the long procession wound from the Technological Institute to the Volkovo cemetery, where Mendeleyev was buried beside Dobrolyubov, Pisarev, Turgenev, and other great Russian men of letters and the sciences. And at the head of the procession there walked a group of students bearing a large board on which Mendeleyev's great discovery the Periodic Law of the Chemical Elements was written.

"And I believe that the day is not far off when a liberated Russia will erect bronze statues in its squares commemorating not only those who fought for civil freedom but also those who fought for the liberation of the Russian mind; and among them will be a monument to Dmitry Ivanovich Mendeleyev."

Morozov's prophecy has come true. The name of Mendeleyev, Russian scientist of genius, patriot, creator of the Periodic Law, is honoured in the Soviet Union. Many chemical institutes bear that name. Mendeleyev prizes are awarded by the U.S.S.R. Academy of Science for outstanding work in chemistry and physics. Many physical-chemistry institutes distribute Mendeleyev grants and scholarships to students. Branches of the U.S.S.R. Chemical Society which bears Mendeleyev's name function all over the country. Soviet scientists, faithful to the behest of Mendeleyev, are striking out along new paths in science and devoting all their creative forces to the welfare of their people.

In an article entitled "Seventy-Five Years of the Periodic Law," Academician A. Ñ. Bach wrote: "The name and deeds of Mendeleyev enjoy universal renown. The Periodic Law discovered by Mendeleyev is part of the life-long stock-in-trade of every chemist, wherever in the world he works. This law is a powerful general conclusion, a weapon for analyzing the enormous arsenal of chemical knowledge accumulated by mankind and greatly enriched every year. The Periodic Law has served and continues to serve as the guiding-star for thousands of new researches and creative investigations in the sphere of chemical, physical, geological, technological and other branches of science." It is to the history of the discovery of this law that the following pages of this book are devoted.

THE PERIODIC LAW

When eighty-six years ago Mendeleyev began to teach at St. Petersburg University, chemistry was still far from being that well-ordered and harmonious branch of science that we know it is today.

In the history of chemistry there have been a number of turning-points when facts gradually accumulated led to the discovery of new laws that govern these facts. The first important advance in the development of chemistry is closely associated with the name of the great Russian scientist, M. V. Lomonosov. In discovering one of the fundamental laws of nature—the law of the conservation of matter—Lomonosov predetermined the development of natural science that followed his discovery so swiftly. To Lomonosov, too, goes the credit for introducing the concepts of the atom and the molecule into chemistry.

When substances react upon each other, the atoms composing them join, divide or re-arrange themselves, thus forming new substances, the number of atoms remaining constant. In that consists the essence of Lomonosov's law of the conservation of matter, as applied to chemistry.

Subsequent work by the British scientist Dalton definitely confirmed the atomic theory in chemistry. Engels wrote that "the atomic theory is the foundation on which the whole of theoretical chemistry is built. That is why a new epoch in chemistry is opened with the atomist." According to this theory chemical elements consist of aggregates of atoms characterized by definite common properties. The atomic theory brought the conception of the atom to the fore in chemistry. It became necessary to study the system of laws that govern the behaviour of atoms, to acquire precise knowledge of what distinguished one atom from another.

After the International Congress of Chemists in Karlsruhe, in which Mendeleyev took an active part, the works of Avogadro and Charles Gerhardt were rescued from oblivion. With their assistance it is possible to determine the relative weights of atoms and molecules. On the basis of Avogadro's law (equal volumes of all gases at the same temperature and pressure contain equal numbers of molecules), Gerhardt drew up a simple formula which made it possible to determine the magnitude of the atomic weight of elements on the basis of the simple relationship between molecular weight and the density of the element in a gaseous state. This method was applied successfully for determining the atomic weight of many elements with densities that could be easily measured. The Avogadro-Gerhardt Law placed in the hands of the chemist the possibility of determining the relative atomic weights, and establishing the difference between one atom and another. Other methods, too, were found for determining atomic weights, such as by their thermal capacity.

One of the most important properties of atoms is their ability to combine with each other. As long ago as 1833 the British chemist Frankland established that each element possessed its own valency. A knowledge of the valencies of any two elements enables one to find the quantitative composition of the substance formed by their combination.

Thus, each element is characterized by two principal properties—the weight of its atoms and the valency. But what determines the valency of the atom? What is the structure of the atom? What do atoms of different elements have in common and where do they vary? All these questions remained unanswered. When Mendeleyev began his scientific career, 64 elements were known to chemistry. The search for new elements was carried out in an unsystematic manner, discoveries were matters of chance, and it was not clear whether an end would ever come to the discovery of new elements.

"The whole essence of theoretical knowledge in chemistry," wrote Mendeleyev, "lies in the abstract conception of the elements. To find their fundamental properties, to determine the reasons for their differences and similarities, and then on the basis of this knowledge to forecast the properties of new bodies formed by the elements—that is the path along which our science advanced firmly ... and there still remains much to be done. The main interest of chemistry is in the study of the principal qualities of elements."

* * *

The great majority of scientists in Mendeleyev's time were firmly convinced that atoms of different elements are in no way connected with each other, being quite independent particles of nature. Only a few advanced scientists realized that there must be a general system of laws regulating the behaviour of the atoms of each and every element. However, the few attempts made by Béguyer de Chancourtois, Newlands, Lothar Meyer and others to find a system of laws governing the behaviour of atoms—attempts carried out in isolation from the fundamental properties of atoms—were unsuccessful and exercised no influence on Mendeleyev, the future founder of the Periodic System of the elements.

When, in 1868, Mendeleyev started his course of lectures on chemistry at St. Petersburg University, he was only able to make the bitter statement that "our knowledge of the quantitative aspect of chemical transformations is far in advance of our knowledge of qualitative relations." He felt certain that "the assembling of facts, even on a very large scale, mere accumulation, even when done in a spirit of devotion to science, is not enough to give us a method for mastering science; it will not provide either a guarantee for successes in the future or even the right to the name of science in the highest sense of the word. The palace of science needs not only material but a plan, it needs harmony; it is built by the labour that is needed to prepare material as well as to lay it in place, to work out the plan itself, to combine the parts in a harmonious whole, to point out the ways where the most useful material can be obtained."

But Mendeleyev was not the type of scientist who is content merely to point to the one-sidedness of chemical knowledge. "Mendeleyev was a man who could not bear any kind of disorder or chaos," writes Academician A. A. Baikov. "It was clear to me that as a profound thinker and man of science he could not allow the existence of disorder and chance in nature; he was one who maintained that if we see disorder and chaos in nature then it exists not there but in our imperfect understanding of that nature. That is why at the beginning of his course in chemistry at St. Petersburg University, where he had been appointed to the chair of chemistry, Dmitry Ivanovich had to establish order in the chemical elements."

As already mentioned, Mendeleyev's work on his *Foundations of Chemistry* had led him directly to the discovery of the laws regulating the inner connections between chemical elements. However, many years of work methodically embracing the most remote fields of chemistry and natural science as a whole were required before he could achieve his great discovery.

"Undertaking the compilation of the manual of chemistry called the *Foundations of Chemistry*," Mendeleyev wrote, "I had to draw up some kind of system of simple bodies so that in placing them I had some definite point to start from and was not guided by pure chance as if following my instinct.... Any system that is based on accurately observed numbers is, of course, for that alone preferable to other systems that have no numerical basis, since there will be less room in it for arbitrariness.... The numerical data relevant to simple bodies are at present limited....

"Optical properties, for instance, and even electrical and magnetic properties cannot, of course, serve as the basis of a system because one and the same body can show great differences in this respect, according to the state in which it happens to be. It suffices to recall in this respect graphite and diamond, ordinary and red phosphorus, oxygen and ozone.... Yet each of us realizes that with all the changes in the properties of simple bodies in a free state, something remains constant, and when an element is changing by combination this something is material and shows the characteristic of the combination in which the particular element is contained. In this connection we know now only one numerical datum—the atomic weight peculiar to the element. That is why I have tried to found a system of classification according to the atomic weights of the elements."

By comparing the chemical properties of different elements, researchers had long ago discovered that elements could be placed in several groups according to similarity in their properties.

For example, there is the group of alkali metals: lithium, sodium, potassium, rubidium and caesium. In their chemical properties all the elements in this group are practically identical: they are all 1-valent, they all react violently both with water and oxygen, and are thus found in nature only in the form of combinations. They form strongly alkaline hydroxides.

Another group is the halogens: fluorine, chlorine, bromine and iodine. They are all non-metallic elements, they react equally violently with other elements, and for this reason they, too, are not found in the free state in nature; in combination with hydrogen they form non-oxygen acids. These elements do not combine with oxygen directly. Oxides of the halogens, combined with water, form not the bases but the oxygen acids.

Besides these two groups of similar elements there are other groups of alkaline earth elements, a sulphur group, a phosphorus group, etc. Before Mendeleyev, all scientists, when searching for a classification of the elements, tried to unify similar elements and thus obtain small "natural groups" but they did not look for the connections between these "natural groups."

Mendeleyev chose a way that was fundamentally different. "In the comparison of dissimilar elements, I believe, lies the main difference between my system and those of my predecessors," he wrote. "With few exceptions I accepted the same groups of analogous elements as they did, but I set myself the aim of studying the system of laws regulating the reciprocal relations of these groups. Thus I arrived at the aforementioned general principle which applies to all elements and embraces many previously accepted analogies and permits of such conclusions as were impossible before. . . . The atomic weights of dissimilar elements in the system were not compared with one another; yet it is just the dissimilar elements which reveal the natural dependence of properties on changes in atomic weight."

Listing the elements according to their differences in atomic weight and placing other groups after the two groups of similar elements—the halogens and alkali metals—Mendeleyev noticed that these natural groups tended to form a general series of elements which clearly showed the presence of a law of the changing properties of elements: namely, the properties of the elements in this series recur periodically.

Mendeleyev arranged all the sixty-four elements then known in a single system in order of atomic weight. The so-called natural groups of elements entered this system organically and lost their artificial disconnection to reveal that they were fully subservient to the general periodic system.

By analyzing the sequence of elements thus obtained Mendeleyev discovered the Periodic Law.

"In proportion to the increase in atomic weight elements at first acquire entirely new, changing properties, then these properties recur in a new period, in a new line and row of elements and in the same sequence as in the preceding row. Thus the law of periodicity may be expressed as follows: *the properties of the elements, and thus the properties of simple or compound bodies of these elements, are dependent in a periodic way (recur regularly) on the magnitude of the atomic weight of the elements.*"

In the Mendeleyev system the element to stand immediately after hydrogen—the lightest of all—was the alkali metal lithium (helium was still undiscovered), then the alkaline earth metal beryllium, followed by elements with gradually decreasing metallic properties and increasing non-metallic properties—boron, carbon, nitrogen, oxygen and fluorine. Fluorine is already a typical, highly active non-metal. The first element in the next row is sodium, a typical alkali metal whose chemical properties closely resemble those of lithium. Then comes magnesium whose properties closely resemble those of beryllium, followed by aluminium, silicon, phosphorus, sulphur and the analogue of flourine—chlorine. The next element—potassium—is the analogue of lithium and sodium, and so on. Set out by Mendeleyev as a table, the Periodic System of classifying the elements illustrates the law of periodicity of their properties.

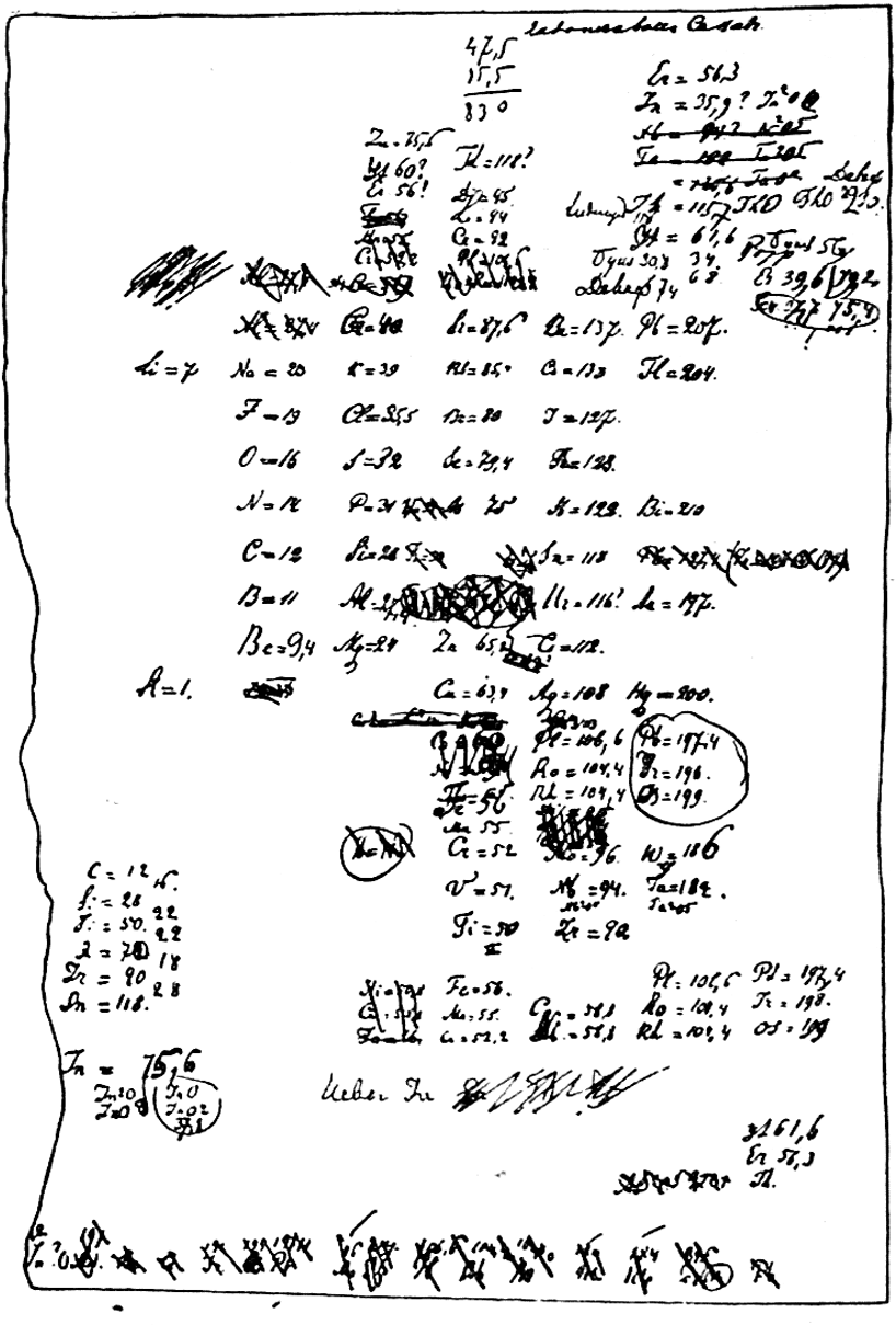
It may easily be seen how in the natural sequence of elements arranged in order of increasing atomic weight, the elements with closely similar properties recur after seven or seventeen elements.

The present Periodic System of the elements is, naturally, different from the first table drawn up by the great man of science almost eighty-six years ago. All its gaps are now filled and from it one can learn the periodicity of properties of the elements in the clearest possible way. But with only sixty-four elements in his table Mendeleyev needed to have keen insight to perceive the periodic dependence. Moreover, the atomic weight of nine of these elements had been calculated erroneously. Twenty-eight elements unknown at that time were located at the beginning and in the middle of the Periodic System, and their absence led to an apparent discrepancy in the Periodic Law.

* * *

The story of how Mendeleyev established the Periodic System of the elements has for long been a matter of great interest to research workers. Mendeleyev himself told some of the story in articles elucidating the idea of the important law he had discovered. But the main question—how the Periodic System was drawn up—remained unexplained. In their search for an answer to this question Soviet historians of natural sciences turned to the vast legacy of writings left by Mendeleyev. The great scientist published over five hundred scientific works, among them books of over a thousand pages. Still more extensive are the works left in manuscript, containing much preparatory material and rough notes. From this vast quantity of manuscripts researchers were recently able to extract some highly valuable new material which after exhaustive analysis was published in 1950.

Close study of the documents concerning the table showed how persevering and energetic was the work that Mendeleyev put into his search for the correct placing of each element. To facilitate this work, he used cards; each card bore the name of an element, its atomic weight and the formulas of its most important combinations.



47,5
15,5
83 0

Er = 56,3
Yt = 60?
Er 56!
In = 75,6
Th = 118?
Di = 95
La = 94
Ce = 92

Ca = 40 Sr = 87,6 Ba = 137. Pb = 207.

Li = 7 Na = 23 K = 39 Rb = 85,4 Cs = 133 Tl = 204.

F = 19 Cl = 35,5 Br = 80 J = 127.

O = 16 S = 32 Se = 79,4 Te = 128.

N = 14 P = 31 75 Sb = 122. Bi = 210

C = 12 Si = 28 Sn = 118

B = 11 Al = 27,4 Ur = 116! Au = 197.

Be = 9,4 Mg = 24 Zn 65,2 Cd = 112.

H = 1.

Cu = 63,4 Ag = 108 Hg = 200.

Pd = 106,6 Pt = 197,4
Ro = 104,4 Ir = 198.
Rh = 104,4 Os = 199.
Fe = 56
Mn 55
Cr = 52 Mo = 96 W = 186
V = 51. Nb = 94. Ta = 182.
Ti = 50 Zr = 90

C = 12 16.
Si = 28 22
Ti = 50. 22
? = 70 18
Zr = 90 28
Sn = 118.

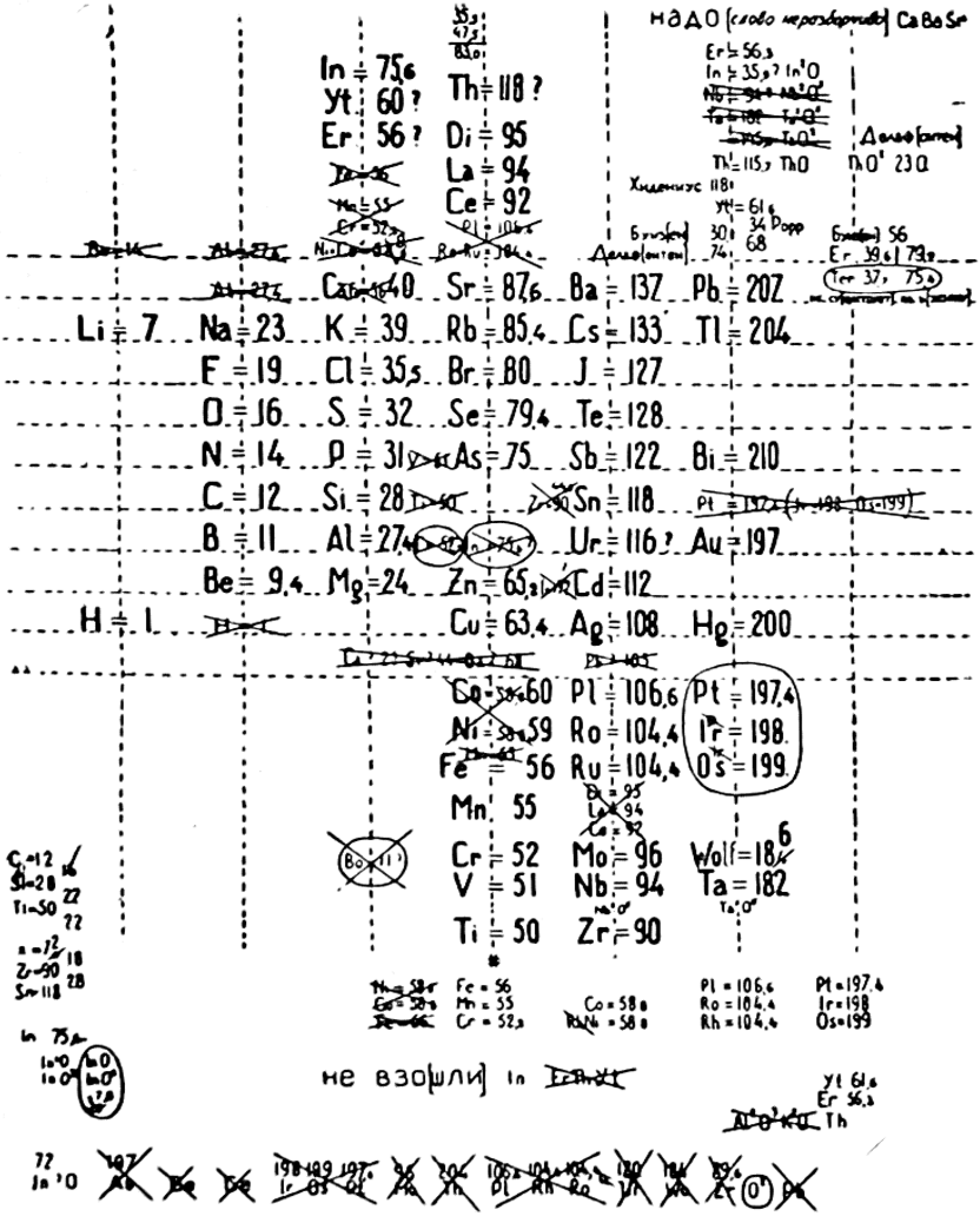
Fe = 56. Pt = 106,6 Pl = 197,4
Mn = 55. Co = 58,8 Ro = 104,4 Ir = 198.
Cr = 52,2 Ni = 58,8 Rh = 104,4 Os = 199

In = 75,6

Ueber In

Er 56,3

Sketch of the first draft of the Periodic System of the Elements



надо [слово неразборчиво] Ca Ba Sr

Er = 56.3
In = 35.? In'O
Th' = 115.? ThO
Хлиенмус 118
Yt' = 61.6
ThO' 230

		In = 75.6	Th = 118?		
		Yt = 60?	Di = 95		
		Er = 56?	La = 94		
			Ce = 92		
		Ca = 40	Sr = 87.6	Ba = 137	Pb = 207
Li = 7	Na = 23	K = 39	Rb = 85.4	Cs = 133	Tl = 204
	F = 19	Cl = 35.5	Br = 80	J = 127	
	O = 16	S = 32	Se = 79.4	Te = 128	
	N = 14	P = 31	As = 75	Sb = 122	Bi = 210
	C = 12	Si = 28		Sn = 118	~~Pt = 197.4 (Ir = 198 Os = 199)~~
	B = 11	Al = 27.4		Ur = 116?	Au = 197
	Be = 9.4	Mg = 24	Zn = 65.2	Cd = 112	
H = 1			Cu = 63.4	Ag = 108	Hg = 200
			Co = 60	Pl = 106.6	Pt = 197.4
			Ni = 59	Ro = 104.4	Ir = 198
			Fe = 56	Ru = 104.4	Os = 199
			Mn 55	~~Di = 95 La = 94 Ce = 92~~	
		~~Bo 11~~	Cr = 52	Mo = 96	Wolf = 186
			V = 51	Nb = 94	Ta = 182
			Ti = 50	Zr = 90	

C = 12 16
Si = 28 22
Ti = 50 22
= 72 18
Zr = 90 28
Sn = 118

In 75.6
InO InO'

Fe = 56
Mn = 55
Cr = 52.3

Co = 58.8
~~Ni~~ = 58.8

Pl = 106.6
Ro = 104.4
Rh = 104.4

Pt = 197.4
Ir = 198
Os = 199

не взошли] In

Yt 61.6
Er 56.3
Th

72
In'O

Key to the first draft of the Periodic System

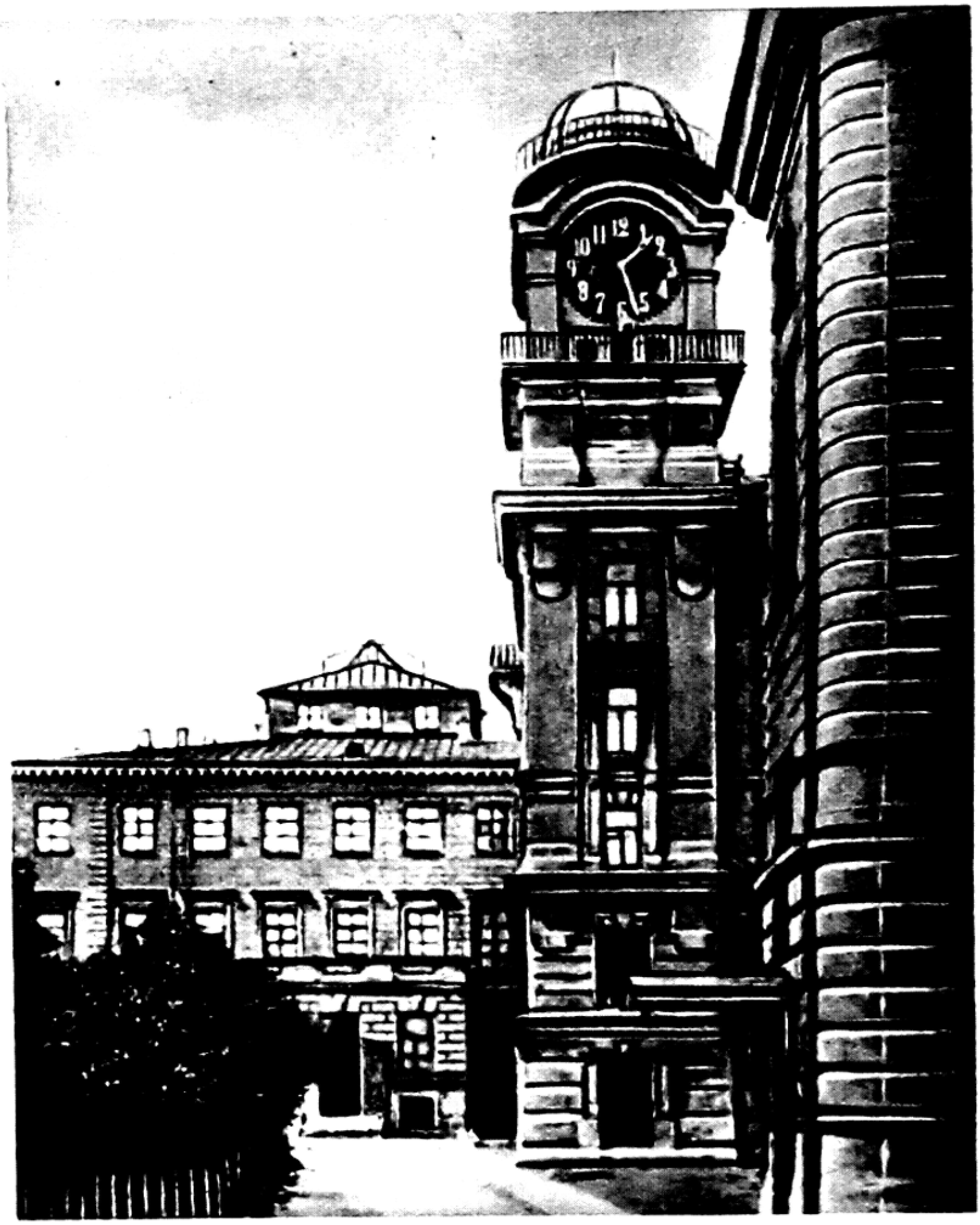
Incedentally, none of these cards have yet come to light in the Mendeleyev archives.

We have an interesting reference to these cards in Mendeleyev's own hand. Shortly before his death he wrote: "Involuntarily the thought is arising that there must exist some connection between the mass and the chemical element, and that as the mass of a substance, although not absolute but only relative, is finally expressed in the form of atoms, we should look for a functional relationship between the individual properties of the elements and their atomic weights. There is only one way to search for anything—even if only for mushrooms or for a dependence—and that is by looking for it and testing. So, I began to arrange material, writing on separate cards the names of the elements with their atomic weights and principal properties, similar elements and close atomic weights, and that soon brought me to the conclusion that the properties of the elements stand in periodical dependence on their atomic weight. And though there were doubts in my mind about many unclear points, not for a moment did I feel any doubt about the general application of the conclusion I had reached, for there could be no question of a chance mistake."

The rough notes for the table that were found show that with the very aim of comparing halogens with alkali metals by their atomic weights Mendeleyev had placed a halogen under each alkali metal (except lithium) in the order of increasing atomic weight. This revealed that the atomic weight of each halogen was several units less than that of the alkali metal above it. After he had filled the second row of the table with halogens, Mendeleyev filled the third row with the elements in the oxygen group, all of which, with the exception of tellurium, possess atomic weights less than those of the halogens in the second row. The same pattern appeared during the completion of the following rows. And Mendeleyev drew the only correct though far from obvious conclusion:

D. I. Mendeleyev (from a portrait by N. Yaroshenko)

Mendeleyev's study at St. Petersburg University



The Main Chamber of Weights and Measures

"Elements, arranged according to magnitude of their atomic weight, show a distinct periodicity in their properties." This rough table apparently served as a foundation for the table published by Mendeleyev in 1869.

As the result of further work Mendeleyev placed in the table all elements known at that time. In doing so he was not bound by any preconceived idea, he adopted no dogmatic attitude towards solving the problem before him. When we examine the first version of the table in its rough and complete forms we see that the solution of the problem about the position of the elements in the Periodic System on the one hand, and the calculations of their atomic weights on the other hand, were for Mendeleyev indissolubly linked in a single process.

Analyzing the chemical properties of beryllium or, as it was then called, glucinium, and looking for its correct place in the table, Mendeleyev found that according to its properties this element should be in a different place in the table than its established atomic weight indicated. He decided that the atomic weight of beryllium had been wrongly calculated and that it ought to have a maximum valency not of 3 but of 2, with an atomic weight not of 13.7 but of 9.4. For similar reasons Mendeleyev changed the atomic weight of calcium from 20 to 40. Against the symbols of those elements which, in his opinion, had been given inaccurate atomic weights, he placed question marks, and these may be seen against gold, platinum, osmium, iridium, yttrium, indium, erbium, etc. In his later works Mendeleyev boldly altered the atomic weight of these elements and on the basis of the elements' chemical properties placed tellurium before iodine, and cobalt before nickel, although by their atomic weights their order should have been reversed. Such was the profound confidence Mendeleyev had in the correctness in his law of periodic change in the properties of the elements.

The place occupied by the element in the table determines its properties. The Periodic Law "... does not describe the multiple function... as a purely chemical law proceeding from a notion of the atoms and particles, combined in multiple proportions interruptedly (and not continuously) ... so that each period contains only a definite number of members." It follows that, if one knows the interval at which the properties of the elements recur, one can tell whether there are still undiscovered elements lying between them. Knowing, for instance, that the atomic weight of calcium is 40 and that it forms the oxide CaO, while the atomic weight of titanium is 48 and it oxidizes as TiO_2 Mendeleyev had all the grounds for stating that there must be an intermediate element between calcium and titanium with an atomic weight of 45, oxidizing as X_2O_3. So Mendeleyev left a place in his table for that still unknown element.

In the table Mendeleyev published in 1869 there were six gaps. These were left for still undiscovered elements with atomic weights of 8, 22, 45, 68, 70 and 180. For the first time in history, chemistry had definitely foreseen, had, so to say, "planned" the discovery of elements and even predetermined their atomic weights. Already in his first work devoted to the Periodic Law, published in 1869, Mendeleyev wrote: "We must expect the discovery of many simple substances that are still unknown to us, such as, for instance, elements similar to Al and Si occupying the places 65-75." In this work, as elsewhere, Mendeleyev reveals himself to be a materialist and dialectician, unconsciously applying the law of the change of quantity into quality, the law of the unity of opposites. This enabled him to discover the profound organic connection between all the elements.

He dated his table: 17/II/1869.

Fully aware of the importance of his discovery Mendeleyev did not wait for the appearance of his *Foundations of Chemistry* but immediately after completing work on the table had it printed in loose leaf and, in February 1869, circulated it among all the physicists and chemists of his acquaintance. On March 18, 1869, at a meeting of the Russian Chemical Society, Professor N. A. Menshutkin read for Mendeleyev who was absent through indisposition, his report entitled "An Outline of the System of the Elements, Based on Their Atomic Weights and Chemical affinities." In this report Mendeleyev gave a detailed explanation of the essence of the Periodic Law and deciphered the table of elements on the basis of this law that he had printed on a "separate sheet."

The following years found Mendeleyev still at work on making his table of elements more precise; he reached a number of conclusions based on the law. Early in 1871 he prepared an article for publication that summarized his numerous experiments connected with the discovery of the Periodic Law—"The Periodic Dependence for Chemical Elements." As he himself wrote, this article was "the best summary of my views and conceptions about the periodicity of elements and the original from which so much was written later about this system. It was the main reason for my scientific fame."

The table of elements accompanying this article differed considerably from the first version and closely resembles the one we know today. Whereas in the 1869 version groups of similar elements were arranged horizontally and the periods vertically, in this table they were placed in a more convenient way: groups of similar elements were placed in vertical rows, the periods horizontally. This allows the table to show more precisely the chemical properties of the group and the periodicity of the change of properties of elements during their passage from one period to another.

In this table Mendeleyev for the first time divided the rows into even and uneven ones. He moved all the elements of the uneven rows in the places to the right and thus formed inner sub-groups of elements with affinities in properties. At the beginning of each group he showed the maximum valency of the elements compared with oxygen, and, beginning with the fourth group, with the valency of hydrogen.

* * *

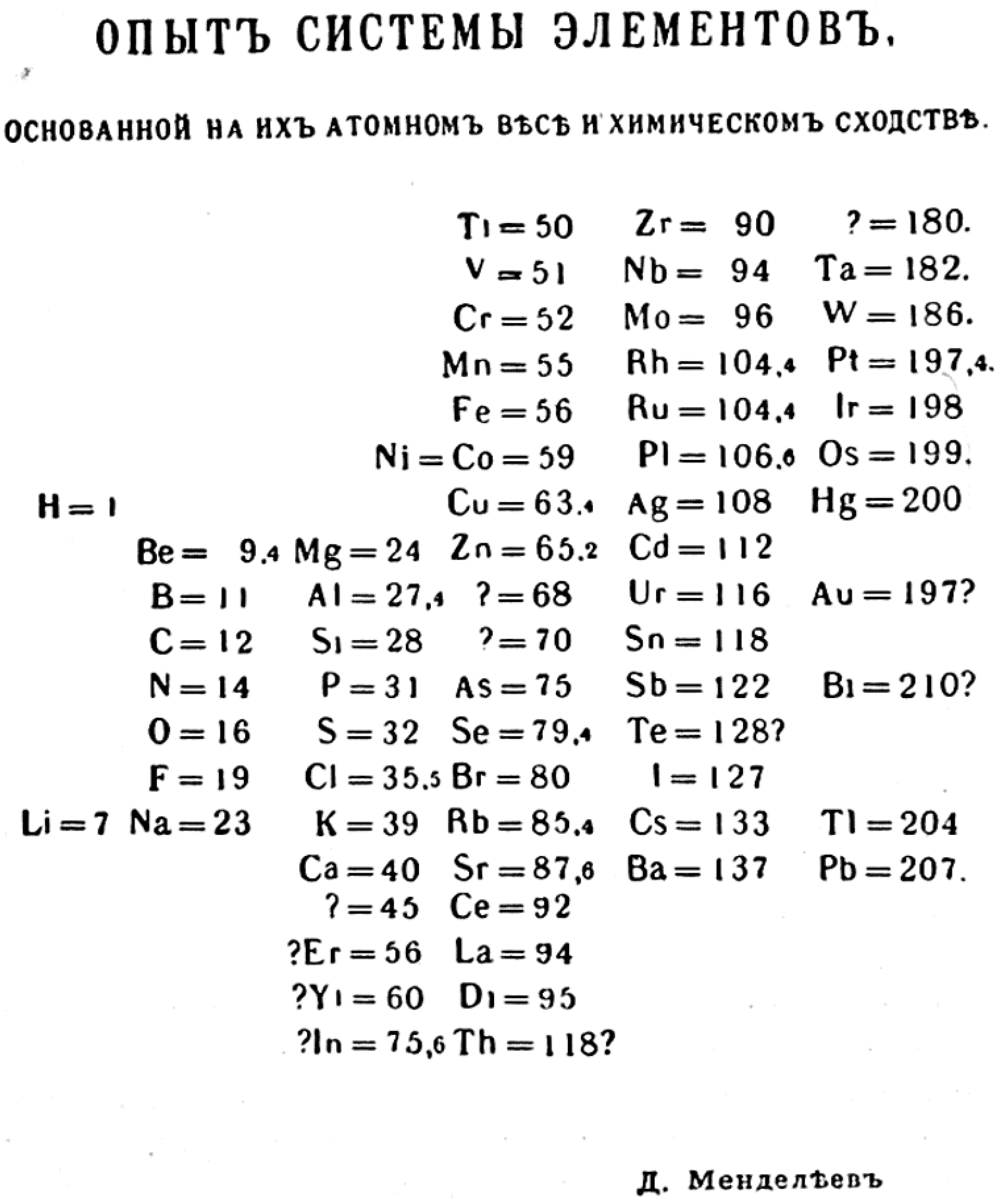
Mendeleyev went on developing his earlier conception of the existence of undiscovered elements. In 1869 he had suggested the existence of six still unknown elements; in the table accompanying his article "The Periodic Dependence for Chemical Elements," however, he left sixteen empty places in the middle of the table and, in addition, conjectured the existence of five transuranic elements.

Mendeleyev used the Periodic Law as an instrument of knowledge. As he wrote: "Confirmation of the law is possible only with the help of conclusions drawn from it—conclusions that would not be possible or could not be expected without it—and with the controlling of those conclusions by experiment." And Mendeleyev, analyzing his law, "drew from it the logical consequence which could prove it true or fallacious." Thus the discoverer himself boldly submitted his theory to the test of practice.

Mendeleyev demonstrated the omnipotence of the human mind and the boundless possibilities of man to penetrate the very essence of things and phenomena; and this he did at a time when a host of idealist agnostics were repeating their assertions that human reason was powerless to do so, that there existed some insurmountable barrier between visible phenomena and their essence, and even that things and phenomena had no essence other than their outer appearance.

In his article "The Periodic Dependence for Chemical Elements" Mendeleyev dwelt in detail on the question of the application of his law for the definition of the atomic weights of little known elements, for correcting the atomic weights of a number of elements and, finally, for determining the properties of still-undiscovered elements.

Hitherto, researchers had not been able to place full confidence in the accuracy of the atomic weights they had given to newly-discovered elements, and this led to contradictions and confusion. After Mendeleyev's discovery the situation changed radically. The Periodic System of



ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ,

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

			Ti = 50	Zr = 90	? = 180.
			V = 51	Nb = 94	Ta = 182.
			Cr = 52	Mo = 96	W = 186.
			Mn = 55	Rh = 104,4	Pt = 197,4.
			Fe = 56	Ru = 104,4	Ir = 198
			Ni = Co = 59	Pl = 106,6	Os = 199.
H = 1			Cu = 63,4	Ag = 108	Hg = 200
	Be = 9,4	Mg = 24	Zn = 65,2	Cd = 112	
	B = 11	Al = 27,4	? = 68	Ur = 116	Au = 197?
	C = 12	Si = 28	? = 70	Sn = 118	
	N = 14	P = 31	As = 75	Sb = 122	Bi = 210?
	O = 16	S = 32	Se = 79,4	Te = 128?	
	F = 19	Cl = 35,5	Br = 80	I = 127	
Li = 7	Na = 23	K = 39	Rb = 85,4	Cs = 133	Tl = 204
		Ca = 40	Sr = 87,6	Ba = 137	Pb = 207.
		? = 45	Ce = 92		
		?Er = 56	La = 94		
		?Yt = 60	Di = 95		
		?In = 75,6	Th = 118?		

Д. Менделѣевъ

"An Outline of the System of the Elements"—a sheet circulated by Mendeleyev to Russian physicists and chemists the elements, fixing the place of every element, provided the possibility of verifying their atomic weight.

Mendeleyev showed that mistakes had been made in the atomic weights of osmium, iridium, platinum, gold, indium, uranium, cerium, lanthanum, erbium, yttrium and thorium. Placing these elements in corresponding groups and rows in the periodic table Mendeleyev gave to each one its new atomic weight calculated by him. These calculations were brilliantly verified. When, later, the inert gases were discovered Mendeleyev placed the element argon before potassium in the table, although according to the atomic weights potassium should have been placed first. It was the chemical properties of the elements that justified Mendeleyev's decision. In later research by many experimenters, of which we shall have more to say later, reasons were found for this disparity in the atomic weights of argon and potassium. In 1869—forty-five years before the work of the British scientists Rutherford, Moseley and others on the theory of the structure of the atom—Mendeleyev with trully amazing insight noted the existence of natural laws that were unknown to science at that time.

In 1871, Volume III of the Journal of the Russian Chemical Society published an article by Mendeleyev entitled "The Natural System of Elements and Its Application for Indicating the Properties of Undiscovered Elements." In this article Mendeleyev provided a detailed description of the chemical and physical properties of still unknown elements. He reasoned as follows: "If in a certain group we find the elements R_1, R_2 and R_3, and if in the row where one of these elements, say R_2, lies we find the element Q before it and element T after it, then the properties of R_2 are determined by the properties of R_1, R_3, Q and T. Thus, for instance, the atomic weight of R_2 equals 1/4 (R_1 plus R_3 plus Q plus T)." The valency of an element is also defined by its place in the table.

Not wishing to introduce into scientific parlance new names for elements still undiscovered, Mendeleyev called them after the element occupying the next lower position in the same group in the Periodic System, adding the prefix eka (sanscrit for plus one). Thus the word eka-aluminium signified aluminium plus one.

Mendeleyev described in more detail the properties of the three elements he called eka-boron, eka-silicon and eka-aluminium. His description of eka-boron ran as follows: "Since it (eka-boron) follows K (39) and Ca (40) and is followed by Ti (48) and V (51) then its atomic weight must be approximately Eb (44).... Its oxide must have the formula Eb_2O_3 and will be basic but not very active. This metal will be nonvolatile, it will not break up water into hydrogen and oxygen under usual temperatures, but under certain high temperature will do so..." etc.

Not being content merely to describe the properties of new elements, Mendeleyev also indicated the most likely way for discovering them. Thus, he wrote, the properties of eka-aluminium "in all relations ought to show the transition from the properties of aluminium to those of indium. In all likelihood this metal will be more volatile than aluminium and thus it may be hoped that it may be discovered by spectral analysis...." Eka-boron, however, is nonvolatile and "consequently, it is not likely to be discovered by the usual means of spectral analysis.... There is, however, reason to believe that the salts of eka-boron will be sufficiently volatile to be discovered by spectral analysis."

Mendeleyev turned over his theory to the experimenters, quite confident of the results. Now research workers all over the world could take part in the search for new elements. If they succeeded, it would mean the complete vindication of the Periodic Table, if not it would be discredited. Mendeleyev awaited the results with impatience.

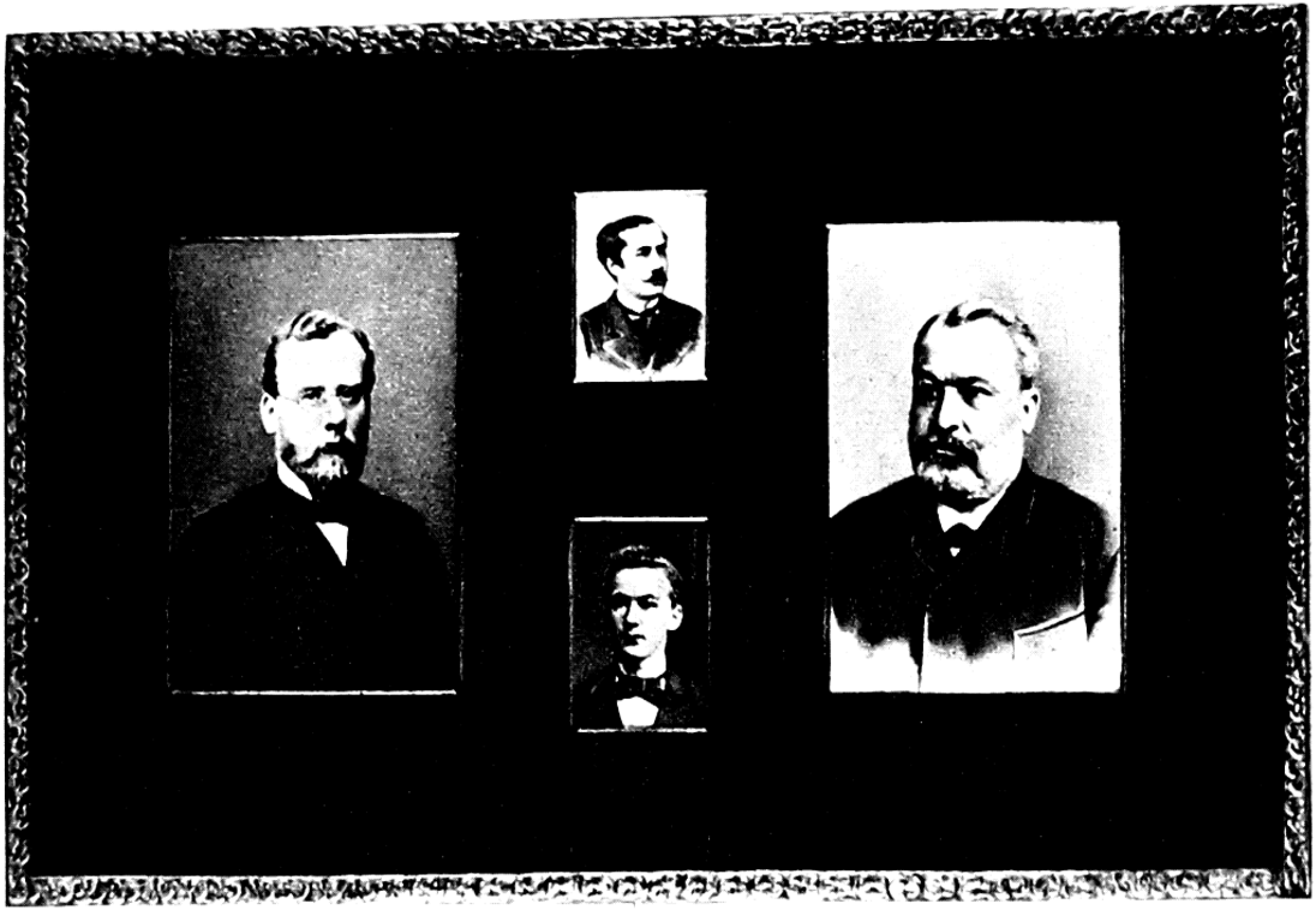
On September 20, 1875, four years after Mendeleyev had published his article, the French chemist Charles Wurtz, at a meeting of the Paris Academy of Science, of which he was a member, read a letter from one of his pupils, Lecoq de Boisbaudran, which ran:

"The day before yesterday, August 27, 1875, between 3 a.m. and 4 a.m. I discovered traces of the probable existence of a new simple body in the products of the chemical analysis of zinc blende from the Pierrefitte mine in the Argelés valley (Pyrenees)." As a mark of honour to his native land de Boisbaudran named the new element gallium.

Not long afterwards de Boisbaudran reported several of the physical and chemical properties of gallium. This metal whose density was given as 4.7 and atomic weight 68 resembled aluminium in its properties.

Mendeleyev, who closely followed world chemical literature, did not miss this announcement. He had not the slightest doubt about the discovery of de Boisbaudran—this element could only be eka-aluminium. The minutes of the proceedings of the Russian Physical-Chemical Society for November 6, 1875, preserve Mendeleyev's report: "D. Mendeleyev drew attention to the fact that the element recently discovered by L. de Boisbaudran and called by him gallium, both by the method of its discovery (spectral analysis of the spark) and by its properties as so far observed, coincides with eka-aluminium, the certainty of whose existence and properties of which were described four years ago by Mendeleyev on the basis of the Periodic Law. If gallium is identical with eka-aluminium then it will have an atomic weight of 68 and a density of 5.9." But the measurements of de Boisbaudran gave the density as 4.7. Who was right: de Boisbaudran who had gallium in his hands or Mendeleyev, the bold theoretician?

The whole scientific world followed the course of the unusual contest between Paris and St. Petersburg. And Mendeleyev was proved right. More accurate measurements confirmed his figure. It was a resounding victory for his theory. The experiments to test his theory were continued, involving an increasing number of researchers.



Pamphlet with portraits of the "corroborators of the Periodic Law" drawn up by Mendeleyev: left—K. Winkler, top—Lecoque de Boisbaudran, bottom—B. Brauner, right—L. Nilson

Mendeleyev in the year of his death

In 1880 Nilson and Cleve found in the rare mineral gadolinite a new element which they named scandium after Scandinavia, their native land.

The properties of scandium corresponded exactly with those of Mendeleyev's eka-boron. Nilson wrote: "Thus the clearest possible vindication is given of the ideas of the Russian chemist which enabled him not only to foresee the existence of the named simple substance but to describe its main properties in advance."

The time had come when chemists all over the world realized the magnitude of Mendeleyev's discovery.

In 1885 the German chemist Winkler discovered a third of the elements foreseen by Mendeleyev. This was the Russian chemist's eka-silicon which its discoverer named germanium. Its properties fully corresponded to Mendeleyev's forecast and Winkler wrote with enthusiasm to the great scientist: "I have to inform you of . . . a new triumph for your wonderful discovery and express my respect and devotion."

The scientist's enthusiasm was fully justified: as far back as 1871, Mendeleyev had, on the basis of the Periodic Law, characterized germanium so completely that Winkler had very little to add, as the following table shows:

Mendeleyev's 1871 forecast for eka-silicon	Winkler's 1885-1886 experimental findings on germanium
Atomic weight 72	Atomic weight 72.6
Specific gravity 5.5	Specific gravity 5.35
The metal will not displace hydrogen in acids	The metal will not dissolve in acids
Oxidization formula $ESiO_2$	Oxidization formula GeO_2
Specific gravity of oxide 4.7	Specific gravity of oxide 4.70
Its salts will easily dissolve in water	Germanium salts easily dissolve in water
Chloride—formula $ESiCl_4$, will be a liquid with a boiling point of about 90° and a specific weight of about 1.9	$GeCl_4$ Is a liquid with a boiling point of 83° and a specific weight of 1.887

This constituted a new resounding success for Mendeleyev's Periodic System.

"I doubt whether there could be a clearer proof of the correctness of the theory of the periodicity of elements," wrote Winkler. "It is, of course, more than a simple affirmation of the daring theory, it signifies an outstanding broadening of our chemical horizon, a gigantic step forward in the field of knowledge."

Soon afterwards Mendeleyev wrote as he was preparing for the press a new edition of the *Foundations of Chemistry*: "Recognizing that the experimental way is the only true one I myself carried out all the controls I possibly could and gave to others every opportunity to test the truth or the fallaciousness of the law.... Tests had to be made to decide whether the new support provided by the Periodic Law was to be accepted or rejected; wherever an effort was made experiment vindicated the law.... I never expected to live to see the confirmation of the consequence of the Periodic Law, but reality turned out otherwise. I wrote descriptions of three elements: eka-boron, eka-aluminium and eka-silicon and less than twenty years passed before I experienced the great joy of seeing all three elements discovered."

Of Mendeleyev's forecast of new elements Engels wrote: "Mendeleyev, unconsciously applying Hegel's law of transition from quantity to quality, achieved a scientific feat...."

This scientific feat serves as the best confirmation of the materialistic philosophical thesis that "our knowledge of the laws of nature, tested by experiment and practice, is authentic knowledge having the validity of objective truth, and that there are no things in the world which are unknowable, but only things which are as yet not known, but which will be disclosed and made known by the efforts of science and practice" (Stalin).

Many famous scientists sought ways of classifying the elements at the same time as Mendeleyev. For the purposes of his course on chemistry Professor Lothar Meyer of Breslau University was seeking a more convenient table for classifying the chemical elements. By purely empirical methods he tried to compare groups of similar chemical elements in the general system. He drew absolutely no theoretical conclusions or generalizations from that. It has now been proved that he had been informed by friends in St. Petersburg (Professor Beilstein among them) about Mendeleyev's works before they appeared in print. Mendeleyev's Table of the Elements was laid before the newly organized Russian Chemical Society on March 18, 1869. In February that year the sheet headed *An Outline of the System of the Elements* was circulated to many chemists. Only in the next year, 1870, did Lothar Meyer's article appear, illustrated with a table which, in the main, was similar to Mendeleyev's. The German scientist admitted the priority of Mendeleyev's discovery.

But that admission is not the essence of the matter. The history of science knows cases when two different researchers more or less simultaneously reach the same conclusion—the natural consequence of science having attained a certain level. In this case, however, this is not what happened. In his published work Lothar Meyer, while not denying the existence of a certain regularity in the order of elements accused Mendeleyev of altering the atomic weights of several elements which did not fit into the order that the table forecast. In the chemical journal *Liebig's Annals* Lothar Meyer wrote: "Too much haste was taken to change the hitherto accepted atomic weights on the basis of a somewhat unreliable starting point." Lothar Meyer did not recognize that the periodic table expressed a fundamental natural law.

Writing in 1906 Mendeleyev stated: "Neither de Chancourtois to whom the French give priority in the discovery of the Periodic Law, nor the British candidate, Newlands, nor Lothar Meyer whom some have described as the founder of the Periodic Law took the risk of forecasting the properties of undiscovered elements, or of changing 'the accepted atomic weights of atoms' and in general did not risk considering the Periodic Law as a new, firmly established law of nature, capable of embracing facts that till now have not been generalized, as I have done in my own work since the beginning (1869)."

At the present time Mendeleyev's priority in discovering one of the main laws of nature—the Periodic Law of the Elements—is acknowledged in scientific circles throughout the world.

* * *

Mendeleyev's predictions of the existence of new elements were brilliantly vindicated and the Periodic System enriched by each new discovery.

In 1893, the British scientists Ramsay and Rayleigh discovered in the air the gas argon, in 1895 they discovered helium. In placing these new elements in the Mendeleyev table Ramsay expressed the opinion that there must be elements in nature occupying a place between helium and argon and also after argon. "On the example of our teacher Mendeleyev," he wrote, "I described, as far as was possible, the properties that were to be expected and the supposed relations of a gaseous element which should stand in the table between helium and argon." Ramsay's forecast was also vindicated. Guided in their research by the precise data of the Periodic System, Ramsay and Travers discovered during the years 1895-98 three further elements—neon, krypton and xenon. With helium and argon these inert gases made a new Group O in the periodic table.

In 1913 the British scientists Rutherford and Soddy discovered yet another inert gas—radon.

In 1898-99 radio-active elements were discovered. The Polish physicist Marie Sklodowska and her husband Pierre Curie while experimenting with pitch-blende discovered radium and polonium; soon afterwards actinium and protactinium were discovered. The study of the behaviour of these elements played a prominent part in the development of our conceptions about the structure of matter.

In 1923 Niels Bohr, von Hevesy and Coster discovered the element hafnium. In 1925 the Noddacks discovered rhenium.

In succeeding years twelve more elements were obtained artificially—technetium, francium, prometheum and astatine and also the transuranic group—neptunium, plutonium, americium, curium, berkelium, californium, athenium and centurium.

Of the 37 elements discovered after 1869 Mendeleyev forecast 21. One hundred places in the periodic table used today have been filled. But the path traced by scientists to that achievement has been far from easy. The old conception of the atom and its properties had to be changed, a whole series of established views had to be rejected. This long, difficult path to a new understanding of matter was lit by the beacon-light of Mendeleyev's Periodic System of the Elements.

* * *

The very fact that the Periodic Law existed laid before chemists and physicists new complicated problems of which the principal one was the question that went to the root of the law itself: What was the essence of the affinity between all chemical elements? Why did a change of atomic mass lead to a change in chemical properties?

As we have seen, in the periodic table Mendeleyev admitted certain exceptions in the order of classification of elements. It remained unclear, however, why there were these exceptions.

Mendeleyev indicated the way that researchers ought to set about in examining this problem:

"When, in the future, the time will come to answer such questions as what atomic weight itself expresses, what is the most likely reason for the dependence of properties on weight, why a small change in the weight of the atom leads to a certain periodic change in properties, then we can expect a theoretical definition of the simplest bodies. . . . We may easily suppose . . . that the atoms of simple bodies are complicated substances, formed by the combination of a number of still more minute particles (ultimates), and that what we call indivisible (the atom) is indivisible only by ordinary chemical forces—in the way that particles are indivisible in ordinary physical conditions—a theory which though precarious and arbitrary, the chemist's mind involuntarily accepts. That is why this supposition has recurred in different forms since long ago and my discovery of periodic dependence between properties and weight apparently supports the presentiment, if the word be permitted, so widely felt by chemists."

The path that Mendeleyev pointed to turned out to be the right one. It led to outstanding discoveries in physics and chemistry. The Periodic Law became the basis for the development of the science of the structure of matter. In addition, discoveries in the realm of atomic physics revealed new depths in the meaning of the great law.

By the end of the last century Russian scientists were advancing scientifically based hypotheses about the complex structure of atoms.

Enduring fame in the history of chemistry was achieved by scientist and revolutionary N. A. Morozov. During solitary confinement, between 1884 and 1905, in the Schlüsselburg fortress, he made a number of highly important discoveries in the field of the structure of matter. Studying Mendeleyev's Periodic System of classification, Morozov independently reached the conclusion that the atom possesses a complicated system, being formed of smaller electrically charged particles. Morozov set down his theory of the structure of the atom in a manuscript *The Periodic System of the Structure of Matter*. This contains his ideas about the transmutation of elements, artificially obtained radio-active elements, the existence of supplies of inner-atomic energy. As a book Morozov's work appeared only in 1907. "Only the events of October 1905 gave it its freedom, as they gave me and my other scientific works ours," recalled Morozov later. "I at once set about getting it published."

The Russian revolutionary scientist accurately forecast the way in which science was to develop.

At the end of the 19th century the phenomenon of radio-activity was discovered. In 1896 the French scientist Becquerel while examining the action of uranium salts on photographic plates found that uranium atoms emitted constant rays with properties somewhat resembling X-rays. This phenomenon was studied by the French scientist Pierre Curie and his Polish wife Marie Sklodowska who, in 1908, discovered two new elements with the same properties as uranium—polonium and radium—and described the emission they observed as radioactivity, and uranium and other similar elements as radio-active. As the result of these scientists' research it was established that the phenomenon of radio-activity consisted in the spontaneous disintegration of the atoms of radio-active elements.

The products of this break-up may themselves be radio-active and, in turn, change into other radio-active elements. The series of such transformations is broken when, as the result of radio-active disintegration there is formed a stable, non-radio-active element. The phenomenon of radio-active disintegration was elucidated with the help of Mendeleyev's Periodic Law. When the atom of one element changes into the atom of another element it changes its place in the Mendeleyev Table. The scientists found what is known as the displacement law, the use of which enables the place in the Mendeleyev Table this or that product of radio-active transformation should occupy to be precisely determined.

During their studies of radio-active elements the scientists discovered the existence of twin-atoms. These atoms have identical chemical properties but somewhat different atomic weights. They occupy the same places in the Mendeleyev Table and are known as isotopes.

Later scientists showed that almost all elements have isotopes and that a simple substance is, usually, a combination of several isotopes. Thus hydrogen has three isotopes with weights 1, 2 and 3. At the present time physicists know about 700 different kinds of atoms, each of which has its place in the Periodic System.

Thus the development of the science of radio-activity has led to the collapse of the old conception of the immutability of elements. "The whole fragile fairy-tale about simple, immutable elements in nature vanished like smoke . . ." wrote Academician A. E. Fersman. "And at that very time when the old conceptions were being so decisively shattered and our picture of the world was changing so completely, one leading principle remained in its place, and not only stayed intact as a reliable beacon to human searching but threw an ever brighter beam on this searching. This was Mendeleyev's Periodic Law."

It should be noted that Mendeleyev himself, while working out his Periodic Law, expressed with great insight the idea of the transformation of elements. "Two phenomena observed today—constant weight and the indesintegrability of elements," he wrote, "now stand in close, even historic, connection and if a known element should disintegrate or a new element be formed we cannot deny that it has not changed its weight." Mendeleyev was a genius at anticipating the modern conception about the mutual dependence between mass and energy. He spoke not about the transformation of mass or substance into energy, but about the transformation of motion, on which "everything depends," from one form to another. Mendeleyev at the same time underlined that "weight depends, of course, on a special kind of motion of matter. . . ."

At the end of the 19th century the existence of "atoms" of electricity—elemental charged particles—was discovered. A long series of discoveries led scientists to the view that the atoms of chemical elements must consist of these elemental particles.

In 1912 Rutherford advanced his theory of the structure of the atom according to which the atom consists of a nucleus and electrons. The atomic nucleus is much smaller than the atom itself but contains almost all the mass of the atom. It has a positive electric charge and is surrounded with a cloud of electrons which revolve around the nucleus at a certain distance. The nuclear charge is equal to the sum of the electronic charges. The larger the nucleus, the greater its charge and the number of the electrons it can bind about itself.

Rutherford's pupil Moseley carried out important experiments in determining the nuclear charge of atoms of different elements. He was assisted in this work by the Mendeleyev Periodic Law. And vice versa, the results of Moseley's work revealed the profound physical meaning of the Mendeleyev Law. Moseley proved that the number of the place in which a given element is put (known as the ordinal number) determines the nuclear charge of its atom and thus the quantity of electrons revolving around it.

As has been mentioned, when Mendeleyev drew up his table of elements he made allowances for certain exceptions, placing argon before potassium, cobalt before nickel, tellurium before iodine, although, judging solely by atomic weight, this order should have been reversed. But let us see what charges the nuclei of these elements have. Moseley established that their nuclear charges corresponded exactly to their atomic number. Thus the nuclear charge of potassium (19) is one more than that of argon (18), and so, for that reason, argon has to be placed before potassium in the Periodic Table of classification. Similarly the nuclear charges of iodine and nickel are one more than tellurium and cobalt respectively.

In this way the discovery was made of the property of atoms on which their position in the Periodic System depends: the place of a chemical element in the Mendeleyev system is determined by the size of the nuclear charge of the atom of that element.

Paying a justified tribute to the immortal work of Mendeleyev, Soviet scientists now call the number of an element in the Periodic Table, determining its nuclear charge—the Mendeleyev number.

Starting from a knowledge of the Mendeleyev number, we are able to explain why it is possible to find several isotope-elements in a single place of the Periodic System. In spite of the different mass of isotopes of one and the same element, their Mendeleyev number remains the same. Now we determine the chemical element as an aggregate of isotopes with the same Mendeleyev number.

In his treatise *The Periodic System as the Foundation of Modern Chemistry*, Professor S. A. Shchukarev, who has made a study of Mendeleyev's scientific heritage, wrote: "D. I. Mendeleyev anticipated with his genius the independent argument that lies in the nature of the element still deeper than its weight, and was able to apply it impeccably, but, in the light of prevailing scientific knowledge, he was not able to formulate exactly any theory of ordinal numbers. He waited for an elucidation of this, in his own words, 'major problem,' in connection with further successes in the sphere of knowledge about the elements."

In 1913 the Danish physicist Niels Bohr advanced a new and more truthful model of atomic structure. According to Bohr's theory, electrons revolve about a nucleus in elliptical orbits. When an electron moves from an orbit farther removed from the nucleus to one nearer to the nucleus a definite quantity of energy is irradiated, a multiple of the minimum quantity of energy, called a quantum. When the electron moves from a nearer to a farther orbit, it absorbs no less a definite quantity of energy, also in quanta.

Basing themselves on the Mendeyev Law, Bohr and other scientists defined the structure of the atom's electron-cloud. Bohr showed that their structure was closely linked with the number of the elements in the different periods in the Mendeleyev Table.

In the first period of the table there are two elements —hydrogen and helium. These elements have one "electron-shell"—energy-level—consisting, in the case of hydrogen, of one electron, and, in the case of helium, of two, which is the maximum number of electrons found in the first shell. This kind of electronic surround is highly stable.

Similarly, as the Mendeleyev number for the next element, lithium, is 3, it follows that lithium must have three electrons. Two of these electrons are in the first electron-shell, the third forms a new shell, the second one.

For the next element—beryllium, the Mendeleyev number is 4; consequently beryllium must have four electrons. Two of these in the first electron-shell, two in the second. Each of the following elements—boron, carbon, nitrogen, oxygen, fluorine and neon—adds one additional electron in the second electron-shell. All the ten electrons found in the neon atom are distributed in two electron-shells, two in the first and eight in the second.

The eight-electron-shell is also highly stable.

Sodium, the eleventh element, has eleven electrons and three electron-shells with two electrons in the first, eight in the second and one in the third. As far as argon in the list each following element adds one more electron in the third shell. Argon—with a Mendeleyev number 18 —has eighteen electrons, two in the first shell, eight in the second and eight in the third.

The nineteenth electron of the next element in the table—potassium—is found in a fourth electron-shell and so on.

With the aid of the Mendeleyev system, Bohr determined the atomic structure of all the elements.

Bohr's work made it clear why the properties of elements recur periodically. Let us take the elements of the inert gases group—helium, neon, argon, krypton, xenon, radon. They share the common characteristic of possessing atoms with highly stable electron-clouds. That is why all the inert gases fail to react to other elements.

With the atoms of alkali metals—lithium, sodium, potassium, rubidium and caesium—the outermost electron-shell consists of one electron only. The atom easily releases this electron and turns into a positively charged ion. That is why the alkali metals enter so easily into chemical reactions.

Sodium is a more active metal than lithium because its last electron lies farther from the nucleus than that of lithium and is thus less stable. For the same reason potassium is more active than sodium and rubidium than potassium and so on.

Or take the halogen group—fluorine, chlorine, bromine and iodine. The atoms of each of these elements have seven electrons in the outermost electron-shell. This makes an almost complete electronic structure. Only one more electron is needed to form a stable electronic shell; for that reason the atoms of the halogens strive to capture this electron. In this lies the reason for their high chemical activity. The atoms of the halogens capture electrons more easily than they lose them and hence their properties make them all typical non-metals. Fluorine is more active than chlorine; that is because the electrons in the outermost electron-shell of fluorine are nearer to the nucleus and more firmly established than the electrons of the chlorine atom.

From the above-mentioned examples it is clear that the chemical properties of an element are determined by the outer electron-shell.

In 1923 the Bohr theory was confirmed by an interesting discovery. For many years scientists had been searching in vain for the element with the Mendeleyev number of 72. In its properties this element ought to resemble lanthanum, and it was in lanthanite that the search was made. Bohr, however, calculated the electronic configuration of this element and established the fact that its structure resembled that of zirconium; from this it followed that it would be found not in lanthanite but zircon. In 1923 an element with the Mendeleyev number of 72 was, in fact, discovered in a Norwegian zircon. It was given the name of hafnium.

Later additions to our knowledge of the structure of matter are mainly connected with the study of the atomic nucleus. Here Mendeleyev's great law has served and continues to serve as a guide in experiments on the laws of the world of atoms.

While elucidating the structure of the atomic nucleus science has made gigantic strides forward on the path to mastering atomic energy. In 1919 Rutherford succeeded in carrying out the first artificial transformation of elements; during the bombarding of nitrogen by radio-active particles oxygen was obtained.

In 1933 the French scientists Frédéric and Irène Joliot-Curie discovered artificial radio-activity. This made it possible to obtain artificially radio-activized isotopes of practically all elements known to exist and to create isotopes of elements as yet undiscovered—those that occupy the 43rd, 61st, 85th and 87th places in the Periodic System. At the same time the Joliot-Curies discovered a new type of radio-activity with the emanation of positrons.

Mendeleyev's Periodic System of classifying the elements in the light of the Joliot-Curies' discovery no longer appeared simply as a sequence of 92 elements, in which the elements are placed in order of numbers according to the positive charge of their nuclei and the number of electrons. The periodic system is seen as a sequence of aggregates each of which consists of nuclei of the same charge, though different in weight, and with identical electronic surrounds.

In 1939 by submitting uranium to the influence of elementary particles of the atomic nucleus—neutrons—a new kind of nuclear transformation was observed—the division of heavy nuclei. The achievement of this kind of nuclear reaction opened the direct way to using the energy contained in the atom.

In all these successes a highly important part was played by the Periodic Law—the foundation of the science of the structure of matter.

This great law, discovered by the genius of a Russian scientist in 1869, is no less important in other branches of science.

Soviet scientists remain faithful to the tradition of their great forerunner D. I. Mendeleyev, and under the leadership of the Communist Party of the Soviet Union are to be found in the leading ranks of those who are discovering the secrets of the universe, and devoting all their strength and knowledge to the benefit of their country and people, to the cause of world peace. The most daring of Mendeleyev's dreams have been surpassed by Soviet reality. The ardent faith of the great Russian scientist in his own people and Motherland has been fully justified.

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